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RESEARCH MEMORANDUM

LOW-PRESSURE PERFORMANCE OF DIFFERENT DIAMETER EXPERIMENTAL COMBUSTOR LINERS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

An investigation was conducted to determine the relative performance of geometrically similar experimental combustor liners with different diameters at low-pressure conditions. Data on combustion efficiency and operable fuel-air-ratio range were obtained with seven experimental combustor liners differing in diameter $\left(4\frac{3}{4} \text{ to } 8 \text{ in.}\right)$, in total air-entry-hole area, and in fuel-atomizer capacity. Operating conditions simulated a 5.2-pressure-ratio turbojet engine operating at 85-percent rated rotor speed, flight Mach number of 0.6, and altitudes from 56,000 to 80,000 feet.

An increase in combustor-liner diameter from $4\frac{3}{4}$ to 8 inches resulted in increased combustion efficiency and increased operable fuel-air-ratio and temperature-rise ranges at conditions of either constant mass-air-flow rate or constant liner air velocity. The observed increase in combustion efficiency with increase in liner diameter was more pronounced with conditions of constant liner air velocity than with constant mass-air-flow rate. Variations in combustor total air-entry-hole area and in fuel-atomizer capacity, within the range investigated, had a negligible effect on the performance of the 8-inch-diameter liner. At a simulated altitude of 56,000 feet and for a temperature rise of 680° F, a $4\frac{3}{4}$-inch-diameter liner had a combustion efficiency of 84 percent; a geometrically similar 8-inch-diameter liner, at the same liner air velocity, had combustion efficiencies of 99 and 93 percent at simulated altitudes of 56,000 and 70,000 feet, respectively.

INTRODUCTION

The operation of current turbojet engines at high altitudes is limited to a great extent by combustor performance deficiencies such as low combustion efficiency and flame blow-out. The NACA Lewis laboratory is engaged in research directed toward an understanding of design and operating criteria that will alleviate these performance deficiencies. As part of this research, the investigation reported herein was conducted to determine the effect of combustor-liner diameter on the altitude performance of an experimental combustor.

A knowledge of the influence of combustor size on combustor performance is necessary for a designer to establish the geometry and space requirements of a proposed combustor unit. In general, the size of the combustor is determined from known relations between combustor performance (efficiency and pressure loss) and air velocity within the combustor. Thus, combustor cross-sectional areas have been made as large as practical in order to provide reasonable values of air velocity (ref. 1). References 2 and 3, however, show that, even with a given air velocity, significant effects of combustor size on performance are present. With an annular combustor (ref. 2), higher combustion efficiencies were obtained with a combustor design having a single large primary combustion zone than with one having two smaller zones (double annular design). A similar trend of higher combustion efficiency with larger combustors is indicated in reference 3 from comparisons of the low-pressure combustion efficiency of various commercial and experimental combustors at operating conditions of equal severity. The trends noted in references 2 and 3 were based on comparisons of dissimilar combustor designs and were, therefore, somewhat obscured by the attendant effects of design variables. The investigation reported herein was conducted to obtain the independent effect of combustor diameter on combustor performance at low-pressure conditions.

Four combustor liners of geometrically similar design but of different diameters $\left(4\frac{3}{4}\text{ to 8 in.}\right)$ were tested in a large-diameter (24-in.) combustor housing; and two of these liners were tested in a 7-inch-diameter production-model combustor housing. The combustor-liner design was a modification of an experimental design (ref. 4) that exhibited good combustion efficiency and ease of ignition at low-pressure conditions. Combustion-efficiency data were obtained for a range of inlet-air velocities and fuel-air ratios at inlet-air pressures of 15, 8, and 5 inches of mercury absolute and an inlet-air temperature of 268° F. Air velocities were chosen to bracket those used in current turbojet combustors. The performance of liners differing only in diameter is compared at conditions of both constant mass-air-flow rate and constant liner air velocity. Performance comparisons of different diameter liners having air-entry-hole area scaled to liner cross-sectional area and of 8-inch-diameter liners differing in air-entry-hole area and in fuel-atomizer capacity are also presented. Data obtained with liners installed in the production-model combustor housing qualitatively indicate the effect of combustor-housing diameter on combustor performance.

APPARATUS AND INSTRUMENTATION

Test Installation

Combustor tests were conducted in two test installations differing mainly in combustor-housing size. A diagram of the test installation having a relatively large combustor housing is shown in figure 1(a), and that having a small housing is shown in figure 1(b). Combustor air-supply and outlet ducts of each installation were connected to the laboratory combustion air and low-pressure exhausts systems, respectively. Air-flow rates and combustion-chamber pressures were regulated by means of remote-controlled valves. Electric heaters were used to preheat the combustion air.

Details of the large (24-in. diam. by 30 in. long) combustor housing and combustor assembly (fig. 1(a)) are described in reference 4. The large-diameter housing was used in order to maintain equal static pressures at all air-entry holes for the various combustors. The production-model combustor housing (fig. 1(b)), having a maximum diameter of 7 inches, was obtained from a J33 engine.

Instrumentation

Most of the instrumentation of the two test installations was similar. Air flow to the combustors was metered by sharp-edged orifices (fig. 1) installed according to A.S.M.E. specifications; fuel flow was metered by calibrated rotameters. Combustor-inlet-air temperature was measured at station 1 (fig. 1(a)) and at station 2 (fig. 1(b)) by means of single iron-constantan thermocouples. Combustor exhaust-gas temperature was measured at a plane (station 3, figs. 1(a) and (b)) approximately 27 inches from the fuel-atomizer tip by means of 17 chromel-alumel thermocouples arranged as shown in figure 2. The exhaust-gas temperatures measured by 16 thermocouples, equally spaced along the center lines of two equal areas of the duct cross section, were used in combustion-efficiency calculations. The temperature of the thermocouple located on the duct center line was used for reference only. By means of a suitable switching arrangement, either individual measurements or an average of the 16 thermocouples could be obtained. The thermocouples of each test installation were connected to self-balancing potentiometers.

With the test installation having the large-diameter combustor housing (fig. 1(a)), combustor-inlet-air static pressure and combustor static-pressure loss were measured with absolute and U-tube manometers, respectively, connected to static-pressure taps at stations 2 and 4. With the small-diameter housing (fig. 1(b)), combustor-inlet and -outlet total pressures were measured with absolute manometers connected to total-pressure probes at stations 1 and 4, respectively.

Combustors

A total of seven combustor configurations of different liner diameter, total air-entry-hole area, and fuel-atomizer size were investigated. Brief descriptions of the combustor configurations are given in the following table:

Combustor configuration	Liner diam. at fuel impingement zone, in.	Liner total air-entry-hole area, sq in.	Atomizer capacity, gal/hr (at 100 psi)
1	$4\frac{3}{4}$	22.3	15.3
2	$5\frac{9}{16}$	24.4	15.3
3	$6\frac{1}{4}$	23.4	15.3
4	8	22.3	15.3
5	8	50.2	15.3
6	8	22.3	40.0
7	8	50.2	40.0

All seven combustor liners were tested in the 24-inch-diameter housing, while only liners 1 and 2 were tested in the 7-inch-diameter housing. Design details of the various combustor liners are shown in figure 3. The liner design was adapted from a combustor developed in reference 4 (configuration 87, $6\frac{1}{4}$-in. diam.) and incorporated an ignition and flame piloting region upstream of the normal fuel-spray cone and alternate zones of closely spaced small holes and widely spaced large holes. As shown in figure 3, the fuel-atomizer tip of each liner protruded 1.5 inches into the combustion zone from the upstream end plate; the ignition spark gap was located at a point 1.50 inches from the combustor center line and 2.25 inches from the combustor end plate. With this design of ignition and flame piloting region, ignition was obtained at or below the stable burning pressure limit of the combustor (ref. 4). The use of alternate zones of large and small holes resulted in a relatively low combustor-outlet gas temperature gradient and in cool combustor walls (ref. 4).

In reference 4, the experimental liner was enclosed in the 24-inch-diameter combustor housing shown in figure 1(a). In order to improve the performance of the smaller-diameter experimental liners when installed in the close-fitting combustor housing, the following modifications were made: (1) air-guide tubes were installed at the large air-entry holes in the upstream portion of the liner, (2) air scoops were provided at the small holes in the upstream region, (3) minor alterations in the air-entry-hole distribution were made, and (4) a conical fairing was attached to the upstream end of the liner. A sketch of liners 1 and 2 installed in the 7-inch-diameter housing is presented in figure 4. This modified liner design was used in the present investigation for liners installed in the small-diameter housing. When these liners were installed in the large-diameter housing, the air scoops and the conical fairing were removed. Simplex-type fuel atomizers having 80° spray angles were used with all combustor configurations.

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Combustor liners 1 and 2, made directly adaptable to the 7-inch-diameter housing, were conical in shape; all other liners were cylindrical. Because of the conical shapes involved, size comparisons are based on liner diameters measured at the fuel-spray impingement zone. The combustor liners were fabricated from 1/32-inch-thick sheet steel uniformly perforated with 1/16-inch-diameter holes on equilateral triangular centers 3/16 inch apart. A porcelain cement was used to close the 1/16-inch-diameter perforations on those portions of the liner where perforations were not desired.

PROCEDURE

The basic operating conditions used in this investigation were as follows:

Condition	Combustor-inlet static pressure, in. Hg abs	Simulated flight altitude in reference engine at cruise speed, ft
A	15.0	56,000
B	8.0	70,000
C	5.0	80,000

For all three conditions, combustor-inlet temperature was 268° F, required combustor temperature rise was 680° F, and liner air velocity (calculated on the basis of inlet-air density and of liner cross-sectional area at the plane of fuel-spray impingement) was 175 feet per second. The preceding conditions simulated operation of the combustor liner in a reference turbojet engine having a pressure ratio of 5.2 and operating at 85-percent rated rotor speed and a flight Mach number of 0.6. Combustor performance data were also obtained over a range of fuel-air ratios at various liner velocities both greater and less than 175 feet per second.

Combustion efficiency is defined as the ratio of actual enthalpy rise across the combustor to the theoretical enthalpy rise available from the fuel and was computed by the method of reference 5. Combustor pressure loss is presented in terms of the percentage of combustor-inlet pressure.

Inspection data for the MIL-F-5624A, grade JP-4, fuel used in this investigation are shown in table I.

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RESULTS

With Large-Diameter Housing

Temperature-rise and combustion-efficiency data obtained with the various combustor liners enclosed in the large-diameter test chamber are presented in figure 5; operational data are presented in table II. The air- and fuel-flow ranges investigated with the larger-diameter combustors were limited by the flow capacity of either the air ducting or the fuel atomizer or by flame blow-out. Because of very unstable combustion, no data were obtained with liner 2 at pressures of 8 and 5 inches of mercury.

The data of figure 5 show that an increase in mass-air-flow rate increased combustion efficiency but decreased the maximum temperature rise obtainable with a given liner at constant inlet-air pressure conditions. The data also show that a decrease in inlet-air pressure resulted in decreased combustion efficiency and decreased maximum temperature rise with a given liner at constant velocity. These results were consistent for all liner configurations.

Duplicate data obtained with two of the combustor liners at several operating conditions are presented in figure 6. The check data show an average deviation of ±2 percent in combustion efficiency, and a maximum deviation of 8 percent at constant velocity conditions.

The static-pressure losses of the seven combustor liners are presented in figure 7, in which the pressure loss, in terms of percentage of inlet static pressure, is plotted against combustor-inlet to -outlet density ratio. Since the diameter of the combustor-outlet duct (at station 4, fig. 1(a)) was not varied with liner diameter, the indicated values of pressure loss in figure 7 may be lower for the $4\frac{3}{4}$- and $5\frac{9}{16}$-inch-diameter liners and higher for the 8-inch-diameter liners than they would be if the outlet duct were of the same diameter as the liner.

With all liners investigated, individual exhaust-gas temperatures (measured at station 3, fig. 1(a)) were generally within ±200° F of the arithmetic average temperature of the 16 thermocouples.

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With Small-Diameter Housing

Effect of operating conditions. - Temperature-rise and combustion-efficiency data obtained with liners 1 and 2 installed in the small-diameter housing are presented in figure 8; operational data are presented in table III. Note that, with liners 1 and 2 enclosed in the close-fitting combustor housing, an increase in mass-air-flow rate resulted in increased combustion efficiency but in decreased maximum temperature rise obtainable. A similar trend was observed with the experimental liners enclosed in the large-diameter housing (fig. 5).

The total-pressure loss of liners 1 and 2 (between stations 1 and 4, fig. 1(b)), in terms of percentage of inlet total pressure, is plotted in figure 9 as a function of combustor-inlet to -outlet density ratio.

Effect of liner alterations. - The use of air-guide tubes at the upstream air-entry holes of liners enclosed in a close-fitting combustor housing (figs. 1(b) and 4) was found to have a significant effect on combustor performance. Temperature-rise data for liner 1 with and without air-guide tubes are presented in figures 8(a) and (b), respectively. These data show that, at most of the conditions investigated, the use of air-guide tubes resulted in a substantial increase in maximum obtainable temperature rise. The effect of air-guide tubes on the combustion efficiency of liner 1 is shown in figure 10. These data indicate that the use of air-guide tubes prevented overrich primary-zone mixture conditions at high fuel-air ratios.

When air-guide tubes were used with liners 1 and 2, ignition was obtained at or below the stable burning pressure of the combustor. The performance of liner 1 with no conical fairing and no air scoops at the two upstream rings of small air-entry holes was very erratic, even at condition A. With such a liner, high minimum ignition pressure, small operable fuel-air-ratio range, and carbon deposition on the exterior of the liner wall at the upstream small air-entry holes were encountered.

DISCUSSION

The data of figures 5 and 8 show that the combustion efficiency of each of the combustor liners investigated increased with mass-air-flow rate. It is apparent, however, that this increase in combustion efficiency occurred with an accompanying increase in (1) liner air velocity, (2) combustor pressure loss, and (3) fuel-atomizer pressure drop. In this investigation, these same factors may influence comparisons of performance of combustors with different diameters. Therefore, in order to determine the independent effect of combustor-liner diameter on performance, the following discussion will consider, in turn, (1) the performance of different diameter liners at constant mass-air-flow rates and at constant liner air velocities and (2) the effect of total air-entry-hole area and of fuel-atomizer capacity on the performance of a combustor liner of constant diameter.

Performance of Liners of Different Diameter

Performance at constant mass-air-flow rate. - A comparison of combustion efficiency (from fig. 5) for combustor liners 1 to 4 enclosed 3029 in the large-diameter housing at constant mass-air-flow rates is shown in figure 11. The combustor liners represented had approximately equal total air-entry-hole areas (approx. 23 sq in.) and were equipped with identical fuel atomizers (15.3 gal/hr, 80° spray angle). At any particular operating condition, therefore, the four liners had approximately equal combustor pressure loss (fig. 7) and similar fuel-spray characteristics. Since the air-flow rates were constant, the larger-diameter liners had a lower air velocity than the smaller-diameter liners. The data of figure 11 show that the highest combustion efficiency was generally obtained with the largest-diameter liners and decreased with decrease in liner diameter. The differences in performance of the different diameter liners were more pronounced at the lower-pressure conditions.

Significant variations in operable range with liner diameter were also noted. Figure 5 showed that larger combustors allowed operation at higher values of temperature rise. The reference turbojet engine required a temperature rise of 680° F for steady-state operation at 85-percent rated rotor speed at a flight Mach number of 0.6 and altitudes above the tropopause. In figure 11, the 680° F temperature-rise curve is shown. At an inlet-air pressure of 15 inches of mercury absolute (simulated altitude, 56,000 ft), all combustors would provide the required temperature rise; at 8 and 5 inches of mercury (simulated altitude, 70,000 and 80,000 ft, respectively), the required temperature rise was obtained only with the two larger-diameter combustors.

Combustion-efficiency data obtained with liners 1 and 2 enclosed in the 7-inch-diameter housing at constant mass-air-flow rate are compared in figure 12. Although the reference velocity (based on combustor-housing maximum cross-sectional area) at each air-flow rate was constant, the liner velocity (based on liner cross-sectional area) varied inversely with liner diameter. The data of figure 12 show that liner 2 $\left(5\frac{9}{16}\text{-in. diam.}\right)$, which had a lower liner velocity than liner 1 $\left(4\frac{3}{4}\text{-in. diam.}\right)$ for a given mass-air-flow rate, had combustion efficiencies approximately 5 percent higher than liner 1 throughout most of the fuel-air-ratio range investigated.

These data indicate that, for constant mass-air-flow rate, an increase in liner cross-sectional area results in (1) increased combustion efficiency, (2) increased operable fuel-air-ratio and temperature-rise ranges, and (3) higher altitude operational limits.

Performance at constant liner air velocity. - Combustion-efficiency data obtained with combustor liners 1 to 4 at constant liner air velocity are compared in figure 13. In this comparison, the fuel-atomizer capacity and the total air-entry-hole area were similar for the four different diameter liners. Since the mass-air-flow rate increased with liner diameter (to maintain constant liner velocity), the combustor pressure loss and fuel-flow rates and pressures (hence, atomization) also increased with liner diameter. At constant liner air velocity, the variation in combustion efficiency with liner diameter was more pronounced than at constant air-flow rate; substantial increases in combustion efficiency with liner diameter are indicated (fig. 13). At operating condition A and at a temperature rise of 680° F, an increase in liner diameter from $4\frac{3}{4}$ to 8 inches increased combustion efficiency from 84 to 99 percent (fig. 13(a)). Limited data obtained at other conditions of velocity (fig. 13(b)) and pressure (figs. 13(c) and (d)) also show higher combustion efficiencies for the larger-diameter liners.

As in the case of constant mass-air-flow rate, higher altitude operational limits with the larger-diameter liners are also indicated at constant liner velocity conditions (fig. 13). Here again, all combustors provided the required temperature rise of 680° F at a pressure of 15 inches of mercury (simulated altitude, 56,000 ft), but only the two larger-diameter combustors provided the required temperature rise at 8 and 5 inches of mercury (simulated altitudes, 70,000 and 80,000 ft, respectively).

Combustion-efficiency data obtained with liners 1 and 2 installed in the 7-inch-diameter housing at approximately constant liner velocity are compared in figure 14. The observed increase in combustion efficiency with liner diameter was more pronounced at constant liner velocity (fig. 14) than at constant mass-air-flow rate (fig. 12). This trend is similar to that obtained in tests with liners 1 and 2 installed in the 24-inch-diameter housing (figs. 11 and 13).

With a close-fitting combustor housing, the effect of liner diameter on combustor pressure loss was significant. A comparison of pressure-loss data (fig. 9) shows that the $5\frac{9}{16}$-inch-diameter liner (2) had pressure losses as much as 100 percent greater than those of the $4\frac{3}{4}$-inch-diameter liner (1) at constant mass-air-flow rate. The higher pressure loss encountered with liner 2 cannot be considered to account for its higher combustion efficiency (figs. 12 and 14), since liner 2 gave higher combustion efficiencies than liner 1 when installed in the 24-inch-diameter housing (figs. 11 and 13), in which case pressure losses were approximately equal.

These data indicate that, at conditions of constant liner air velocity, an increase in liner diameter resulted in increases in combustion efficiency, temperature-rise range, and altitude operational limits; these increases were more pronounced than those observed at constant mass-air-flow rates. Because the increase in combustor performance observed in figures 13 and 14 may also be attributed, at least in part, to the attendant increases in combustor pressure loss (figs. 7 and 9) and fuel-atomizer pressure drop (tables II and III), a separate investigation of the magnitude of these effects was undertaken. 3029

Effect of Liner Hole Area and Fuel-Atomizer Capacity

A study of the effect of total air-entry-hole area and of fuel-atomizer capacity on combustor performance was made only with the 8-inch-diameter liner.

Effect of liner total air-entry-hole area on performance. - A comparison of combustion-efficiency data obtained with liners 4 and 5, having total air-entry-hole areas of 22.3 and 50.2 square inches, respectively, is shown in figure 15. The increased air-entry-hole area of liner 5 was obtained by increasing the number of 1/16-inch-diameter holes at each station and by increasing the size of the 5/8-inch-diameter holes, the tubes, and the dilution-air slots of liner 4 (figs. 3(d) and (e)). Both liners were of equal diameter (8 in.) and had 15.3-gallon-per-hour, 80°-spray-angle fuel atomizers. At a given operating condition, liners 4 and 5 had similar liner air velocities and fuel-spray characteristics but differed in combustor pressure loss. The performance of the two liners is compared in the following table:

Liner	Condition A		Condition B	
	Pressure loss, percent	Combustion efficiency, percent	Pressure loss, percent	Combustion efficiency, percent
4	19	99	20	93
5	12	98	13	91

Although the pressure loss of liner 5 was substantially less than that of liner 4, combustion efficiency was affected only slightly.

Combustion-efficiency data obtained with different diameter liners having total air-entry-hole area scaled to liner cross-sectional area are compared in figure 16. Liners 2 $\left(5\frac{9}{16}\text{-in. diam.}\right)$ and 5 (8-in. diam.) had equal ratios (1.00) of total air-entry-hole area to liner cross-sectional area, and both used identical fuel atomizers (15.3 gal/hr, 80° spray angle). Since the mass-air-flow rate and total air-entry-hole area of liner 2 were increased in liner 5, in proportion to the increase in liner cross-sectional area, the percentage pressure losses of the two liners operating at constant liner velocity conditions would be expected to be approximately equal. At operating condition A (fig. 16) and at a temperature rise of 680° F, liner 2 had an indicated pressure loss of approximately 5 percent (fig. 7(b)); liner 5 had a pressure loss of 12 percent (fig. 7(e)). This discrepancy may be due, to a great extent, to the use of a fixed diameter (6.00 in.) combustor-outlet duct (fig. 1(a)).

The data of figure 16 show that, for a temperature rise of 680° F at condition A, liner 5 gave a combustion efficiency of 98 percent; whereas, liner 2 gave a combustion efficiency of 91 percent. In this comparison, where liner air velocity and combustor-liner air-entry-hole area per unit of air flow were approximately constant, the increase in combustion efficiency with liner diameter was accompanied by an increase only in fuel-atomizer pressure drop.

Effect of fuel-atomizer capacity on performance. - The effects of fuel-atomizer pressure drop on the performance of both the high- and the low-pressure-loss combustors (liners 4 and 5) were determined. The 15.3-gallon-per-hour fuel atomizers of configurations 4 and 5 were replaced by 40.0-gallon-per-hour atomizers in configurations 6 and 7; configurations 4 and 6, and 5 and 7, were otherwise identical (figs. 3(d) and (e)). With the large atomizers, only limited data were obtained at condition A (fig. 17). At this condition and at fuel-air ratios less than 0.0087, fuel surging due to fuel boiling within the atomizer assembly resulted in unstable burning. At fuel-air ratios greater than 0.016, combustion air pressure could not be maintained at 15 inches of mercury absolute because of insufficient flow capacity of the exhaust ducting. For these reasons, only a limited range of fuel-air ratio was investigated.

Although the fuel-atomizer pressure drop was considerably different for the two atomizers at comparable operating conditions, the data of figure 17 show that, within the fuel-flow range investigated, the combustion efficiency of the 8-inch-diameter liners was not affected significantly by the change in fuel-atomizer capacity.

Comparison of Liner Performance

Combustion-efficiency data obtained with the seven experimental combustor liners at operating condition A are ploted in figure 18 as a function of liner diameter. These data indicate that liner diameter is an important factor in combustor performance at low-pressure conditions. The observed trend of higher combustion efficiency with the larger-diameter liners of the present investigation substantiates the trend previously indicated by the data of reference 3. 3029

Effect of Combustor-Housing Diameter on Performance

Variations in combustor-housing diameter, relative to liner diameter, may affect (1) inlet-air distribution, (2) direction and depth of air-jet penetration, and (3) over-all combustor pressure loss. A large-diameter (24-in.) combustor housing was used throughout most of the present investigation in order to minimize the effect of housing diameter on inlet-air distribution of the various diameter liners investigated. The air-guide tubes installed at the large upstream air-entry holes of the liners were considered to promote radial air-jet penetration regardless of housing diameter used. The use of air-guide tubes with liner 1 when installed in the 24-inch-diameter housing had no significant effect on combustor performance. With liner 1 installed in a 7-inch-diameter housing, a substantial increase in operable range and in maximum temperature rise obtainable resulted from the use of air-guide tubes (figs. 8(a) and (b)).

The effect of combustor-housing diameter on combustion efficiency of liners 1 and 2 is indicated in figures 19 and 20. At rich fuel-air ratios, approximately equal combustion efficiencies were obtained with either size enclosure. At lean fuel-air ratios, combustion efficiencies were, in general, higher with the 24-inch- than with the 7-inch-diameter housing. These data indicate that the combustors had a leaner fuel-air mixture in the primary zone when enclosed in the close-fitting housing that when enclosed in the large-diameter housing. The restriction placed on the flow of air to the downstream portion of the combustor by the snug-fitting housing and the air scoops would be expected to result in the entry of a greater fraction of the air through the upstream air-entry holes.

The effect of combustor-housing diameter, relative to liner diameter, on combustor pressure loss was very significant. Data obtained with the large-diameter housing (fig. 7) indicate the pressure loss occurring inside the liner and outlet duct only; whereas, data obtained with the 7-inch-diameter housing (fig. 9) include, in addition, the pressure loss due to air flow through a relatively small annular area between the liner and the combustor housing. The isothermal pressure-loss data obtained at a constant mass-air-flow rate of 0.742 pound per second and a pressure of 15 inches of mercury absolute with two different diameter liners enclosed in the two combustor housings are compared in the following table:

Liner	Liner diameter, in.	Isothermal pressure loss, percent of inlet-air pressure	
		24-Inch-diameter housing (fig. 7)	7-Inch-diameter housing (fig. 9)
1	$4\frac{3}{4}$	3.4	6.3
2	$5\frac{9}{16}$	3.0	11.6

The use of the small-diameter housing introduced a substantial increase in pressure loss over that encountered with the large-diameter housing. This additional pressure loss did not contribute to the combustion process, as evidenced by data of figures 19 and 20; thus, combustion efficiency was not increased by the use of the configuration with the higher pressure loss.

SUMMARY OF RESULTS

An investigation was conducted to determine the relative performance of geometrically similar but different diameter $\left(4\frac{3}{4} \text{ to } 8 \text{ in.}\right)$ experimental combustor liners enclosed in both a relatively large-diameter and a close-fitting combustor housing. The following results were obtained at low-pressure conditions:

1. At a constant mass-air-flow rate with the large-diameter housing, an increase in combustor-liner diameter from $4\frac{3}{4}$ to 8 inches resulted in increased combustion efficiency and increased operable fuel-air-ratio and temperature-rise ranges. Similar but more pronounced effects were obtained for conditions of constant liner air velocity.

2. For the range investigated, variations in combustor air-entry-hole area and in fuel-atomizer capacity had negligible effects on the performance of the 8-inch-diameter experimental liner.

3. The effect of combustor-housing diameter, relative to liner diameter, on combustion efficiency was small; but its effect on combustor pressure loss was significant.

4. At conditions simulating a 5.2-pressure-ratio turbojet engine operating at 85-percent rated rotor speed and a flight Mach number of 0.6, a $4\frac{3}{4}$-inch-diameter liner had a combustion efficiency of 84 percent at a simulated altitude of 56,000 feet; a geometrically similar 8-inch-diameter liner had combustion efficiencies of 99 and 93 percent at simulated altitudes of 56,000 and 70,000 feet, respectively. Both the $4\frac{3}{4}$- and the 8-inch-diameter liners had equal liner air velocities.

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CONCLUDING REMARKS

The data presented herein indicate effects of combustor-liner diameter on performance that may not be attributed to changes in liner air velocity, fuel atomization, or combustor pressure drop. The mechanism through which liner diameter (or liner cross-sectional area) may affect combustor performance at low-pressure conditions is not well understood. An approximate estimate of quenching distance for laminar flames (ref. 6) indicates that flame quenching at the combustor wall may account for some incomplete combustion; however, the variation in liner circumference investigated (14.9 to 25.1 in.) is not of sufficient magnitude to account for the observed variation in combustion efficiency. A consideration of the effect of liner cross-sectional area on turbulence characteristics within the combustion zone and the resulting effect of turbulence on the combustion process is limited by insufficient quantitative data. An increase in liner diameter may increase the percentage of fuel evaporated in the upstream portion of the combustor by allowing the fuel-spray droplets to travel a greater distance before impinging on the combustor wall. Reference 7 reports substantial improvements in combustion efficiency at low fuel-flow conditions when losses of unevaporated fuel from the combustion zone were reduced.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 4, 1953

REFERENCES

1. Olson, Walter T., Childs, J. Howard, and Jonash, Edmund R.: Turbojet Combustor Efficiency at High Altitudes. NACA RM E50I07, 1950.

2. Zettle, Eugene V., and Mark, Herman: Simulated Altitude Performance of Two Annular Combustors with Continuous Axial Openings for Admission of Primary Air. NACA RM E50E18a, 1950.

3. Norgren, Carl T., and Childs, J. Howard: Effect of Liner Air-Entry Holes, Fuel State, and Combustor Size on Performance of an Annular Turbojet Combustor at Low Pressures and High Air-Flow Rates. NACA RM E52J09, 1953.

4. Dittrich, Ralph T.: Investigation of Low-Pressure Performance of Experimental Tubular Combustors Differing in Air-Entry-Hole Geometry. NACA RM E53G01, 1953.

5. Turner, L. Richard, and Bogart, Donald: Constant-Pressure Combustion Charts Including Effects of Diluent Addition. NACA Rep. 937, 1949. (Supersedes NACA TN's 1086 and 1655.)

6. Simon, Dorothy M., and Belles, Frank E.: An Active Particle Diffusion Theory of Flame Quenching for Laminar Flames. NACA RM E51L18, 1952.

7. Butze, Helmut F., and Jonash, Edmund R.: Turbojet Combustor Efficiency with Ceramic-Coated Liners and with Mechanical Control of Fuel Wash on Walls. NACA RM E52I25, 1952.

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TABLE I. - FUEL ANALYSIS

Fuel Properties	MIL-F-5624A grade JP-4 (NACA fuel 52-53)
A.S.T.M. distillation D86-46, °F	
Initial boiling point	136
Percent evaporated	
5	183
10	200
20	225
30	244
40	263
50	278
60	301
70	321
80	347
90	400
Final boiling point	498
Residue, percent	1.2
Loss, percent	0.7
Aromatics, percent by volume	
A.S.T.M. D-875-46T	8.5
Silica gel	10.7
Specific gravity	0.757
Viscosity, centistokes at 100 °F	0.762
Reid vapor pressure, lb/sq in.	2.9
Hydrogen-carbon ratio	0.170
Net heat of combustion, Btu/lb	18,700

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TABLE II. - OPERATIONAL DATA FOR DIFFERENT DIAMETER LINERS ENCLOSED IN 24-INCH-DIAMETER HOUSING

[Combustor-inlet temperature, 728° R.]

Run	Combustor-inlet static pressure, in. Hg abs	Mass-air-flow rate, lb/sec	Combustor-liner velocity, ft/sec	Static-pressure loss through combustor, in. Hg	Fuel flow, lb/hr	Fuel-atomizer pressure drop, lb/sq in.	Fuel-air ratio	Mean combustor-outlet temperature, °R	Combustion efficiency, percent
				Liner 1					
205	15.0	0.573	170.6	0.41	15.0	--	0.0073	1155	79.5
206				.45	20.2	--	.0098	1315	82.4
207				.51	26.4	--	.0128	1490	83.3
208				.53	31.2	12	.0151	1615	83.3
209				.58	38.3	17	.0186	1805	83.9
210				.62	44.1	21	.0214	1930	82.6
211				.66	50.2	27	.0243	2060	81.6
212				.68	56.0	35	.0271	2160	79.6
213				.70	59.2	39	.0287	2220	79.0
214		0.571	170.0	0.74	62.5	43	0.0304	2275	77.9
215				.76	66.7	52	.0324	2360	77.7
216		0.740	220.3	0.64	15.3	--	0.0057	1100	87.1
217				.70	21.2	12	.0080	1265	92.0
218				.76	27.4	13	.0103	1395	89.6
219				.82	33.5	14	.0126	1515	87.7
220				.87	40.3	18	.0151	1650	86.7
221				.94	46.4	23	.0174	1760	85.3
222				.99	54.0	32	.0203	1895	84.1
223				1.03	60.5	43	.0227	1990	82.2
233	8.0	0.400	223.3	0.36	18.4	--	0.0128	1100	40.0
234				.40	14.6	--	.0101	1260	72.0
235				.40	11.6	--	.0081	1240	86.6
236				.34	21.0	--	.0146	960	22.0
237	5.0	0.245	219.0	0.19	11.5	--	0.0130	940	22.4
238				.19	13.8	--	.0156	790	5.8
239	15.0	1.187	353.5	1.54	20.0	--	0.0047	1035	87.6
240				1.59	25.3	18	.0059	1130	91.4
241				1.75	33.5	19	.0078	1270	94.3
242				1.89	43.4	22	.0102	1420	94.3
243				2.04	53.4	33	.0125	1550	92.3
244				2.15	62.0	45	.0145	1660	91.2
245				2.24	70.6	57	.0165	1755	89.2
246				2.30	78.7	71	.0184	1820	85.8
				Liner 2					
343	15.0	0.572	124.0	0.37	16.6	24	0.0081	1205	80.5
344				.42	23.1	--	.0112	1440	88.2
345				.45	28.4	--	.0138	1570	86.1
346				.48	33.2	12	.0161	1710	87.1
347				.51	38.6	17	.0187	1840	86.0
348				.54	43.3	21	.0210	1950	85.3
349				.57	49.2	27	.0239	2095	85.3
350				.60	54.4	33	.0264	2185	83.2
351				.64	60.2	41	.0292	2310	82.9
352		0.739	160.1	0.59	17.4	30	0.0065	1160	89.2
353				.66	25.2	17	.0095	1370	93.4
354		0.740	160.3	0.69	30.2	14	0.0113	1475	91.8
355				.73	35.0	15	.0131	1575	90.8
356				.77	41.6	20	.0156	1715	90.3
357				.82	48.8	27	.0183	1855	89.2
358		0.741	160.5	0.87	54.4	34	0.0204	1960	88.6
359				.93	59.5	41	.0223	2050	87.8
360				.96	65.0	47	.0244	2140	86.7
361				1.01	70.8	57	.0265	2240	86.2
372		1.190	258.0	1.45	30.0	22	0.0070	1210	93.3
373				1.55	37.7	20	.0088	1330	93.8
374				1.65	45.2	24	.0105	1440	93.6
375				1.75	53.5	33	.0125	1560	93.5
376				1.86	62.0	46	.0145	1670	92.5
377				1.97	69.3	57	.0162	1765	92.0
378				2.00	76.7	67	.0179	1870	92.5

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TABLE II. - Continued. OPERATIONAL DATA FOR DIFFERENT DIAMETER LINERS ENCLOSED IN 24-INCH-DIAMETER HOUSING

[Combustor-inlet temperature, 728° R.]

Run	Combustor-inlet static pressure, in. Hg abs	Mass-air-flow rate, lb/sec	Combustor-liner velocity, ft/sec	Static-pressure loss through combustor, in. Hg	Fuel flow, lb/hr	Fuel-atomizer pressure drop, lb/sq in.	Fuel-air ratio	Mean combustor-outlet temperature, °R	Combustion efficiency, percent
Liner 3									
408	15.0	0.742	127.5	0.62	18.7	--	0.0070	1215	95.0
409				.68	27.4	--	.0103	1415	93.4
410				.76	37.8	14	.0141	1645	92.4
411				.82	48.4	24	.0181	1855	90.5
412				.87	56.6	34	.0212	2020	90.4
413				.94	66.4	47	.0249	2180	87.9
414				1.00	73.7	58	.0276	2315	87.7
645		0.741	127.3	0.61	17.1	--	0.0064	1140	87.0
646				.65	25.1	--	.0094	1325	87.2
647				.71	33.5	--	.0126	1545	91.3
648				.75	40.0	16	.0150	1690	91.4
649				.81	48.6	24	.0182	1860	90.1
650		0.742	127.5	0.87	57.0	33	0.0213	2030	90.1
651				.94	65.9	46	.0247	2190	89.2
652				.99	73.0	57	.0273	2310	88.1
662	8.0	0.399	128.6	0.39	12.5	--	0.0087	1285	87.6
663				.41	16.1	--	.0112	1420	85.7
664				.44	19.9	--	.0139	1575	86.2
665				.46	23.5	--	.0164	1695	84.5
666				.49	27.9	--	.0194	1835	82.8
667				.51	31.4	--	.0219	1970	83.7
668				.53	34.8	--	.0242	2060	81.9
669				.54	38.0	--	.0265	2160	81.5
670				.57	41.6	17	.0290	2260	80.6
671				.60	45.4	21	.0316	2360	79.6
683	5.0	0.246	126.9	0.24	11.0	--	0.0124	1290	62.6
684				.25	13.8	--	.0156	1320	53.1
685				.25	18.5	--	.0209	1390	45.1
686				.29	22.8	--	.0257	1480	42.4
699	15.0	1.035	178.0	1.21	28.4	--	0.0071	1220	95.0
700				1.28	35.0	14	.0094	1395	98.3
701				1.37	44.1	20	.0118	1535	95.8
702				1.46	52.8	29	.0142	1675	95.0
703				1.53	60.4	39	.0162	1800	95.6
704				1.58	67.1	49	.0180	1890	94.0
705				1.66	74.0	58	.0199	1985	93.0
706				1.72	81.2	70	.0218	2080	92.2
755		1.456	250.5	2.16	25.2	16	0.0048	1075	98.6
756				2.29	38.3	21	.0073	1260	99.1
757				2.51	53.9	31	.0103	1450	97.4
758				2.67	68.2	51	.0130	1620	96.8
759				2.84	80.6	72	.0154	1753	95.6
777	8.0	0.777	250.2	1.27	20.5	--	0.0073	1225	92.1
778		0.774	249.3	1.35	24.9	--	0.0089	1325	91.6
779				1.40	30.7	--	.0110	1455	91.7
780				1.45	37.3	16	.0134	1580	89.7
781				1.52	43.4	21	.0156	1690	88.1
782				1.59	48.4	25	.0174	1780	87.3
783				1.66	53.4	30	.0192	1875	87.1
784				1.71	58.5	36	.0210	1965	86.6
785	8.2	0.774	243.2	1.75	64.0	45	0.0230	2080	86.1

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TABLE II. - Continued. OPERATIONAL DATA FOR DIFFERENT DIAMETER LINERS ENCLOSED IN 24-INCH-DIAMETER HOUSING

[Combustor-inlet temperature, 728° R.]

Run	Combustor-inlet static pressure, in. Hg abs	Mass-air-flow rate, lb/sec	Combustor-liner velocity, ft/sec	Static-pressure loss through combustor, in. Hg	Fuel flow, lb/hr	Fuel-atomizer pressure drop, lb/sq in.	Fuel-air ratio	Mean combustor-outlet temperature, °R	Combustion efficiency, percent
Liner 4									
812	15.0	0.741	77.8	0.57	21.5	21	0.0081	1255	89.8
813				.62	29.7	17	.0111	1465	92.8
814				.68	37.9	19	.0142	1655	93.1
815				.71	45.5	21	.0170	1800	91.0
816				.75	54.1	28	.0203	1975	90.6
817				.80	63.0	39	.0236	2135	89.3
818				.85	70.3	48	.0264	2260	88.3
825	8.0	0.397	78.1	0.35	15.8	--	0.0111	1375	81.2
826				.37	21.2	--	.0148	1600	83.5
827				.40	24.9	--	.0174	1755	85.0
828				.43	29.7	--	.0208	1920	84.4
829				.45	34.3	--	.0240	2040	81.6
830				.48	38.1	--	.0267	2160	81.3
831				.50	41.4	--	.0290	2230	80.9
848	5.0	0.397	125.0	0.56	16.6	--	0.0116	1450	88.2
849				.59	20.2	--	.0141	1570	84.2
850				.62	22.6	--	.0158	1660	84.4
855	8.0	0.865	170.2	1.42	17.1	38	0.0055	1090	89.4
856		0.863	169.8	1.48	24.2	23	0.0078	1270	95.6
857				1.60	33.3	13	.0107	1470	96.8
858				1.68	41.6	16	.0134	1620	94.5
859	8.2	0.863	165.8	1.73	49.9	24	0.0160	1775	94.1
871	15.0	0.741	77.8	0.62	25.2	14	0.0084	1365	92.9
872				.66	32.0	15	.0120	1530	93.6
873				.69	39.4	16	.0148	1680	91.7
874				.73	46.4	21	.0174	1825	91.1
875				.78	53.4	27	.0200	1960	90.2
876				.82	60.5	36	.0227	2090	89.2
877				.87	68.4	46	.0256	2240	89.0
885	8.0	0.397	78.1	0.35	13.5	--	0.0094	1280	80.1
886				.37	16.4	--	.0115	1460	88.8
887		0.394	77.8	0.43	21.5	--	0.0152	1650	86.5
888				.44	24.8	--	.0175	1780	84.9
889				.46	29.7	--	.0209	1900	81.9
890				.47	34.2	--	.0241	2045	81.2
891				.49	38.3	--	.0270	2175	80.9
892				.52	42.4	16	.0299	2285	79.6
893	5.0	0.395	124.5	0.51	11.2	14	0.0079	1190	79.7
894	5.1	0.395	122.0	0.54	15.0	--	0.0105	1360	82.7
895				.57	17.4	--	.0122	1480	85.8
896	5.2	0.395	119.6	0.59	20.2	--	0.0142	1575	84.2
897	5.0	0.248	77.4	0.30	12.4	--	0.0140	1470	74.4
898				.30	15.5	--	.0175	1680	78.0
899	5.1	0.248	76.0	0.31	18.1	--	0.0204	1800	76.3
910	8.0	0.856	168.5	1.41	18.5	28	0.0060	1110	85.7
911				1.46	23.5	20	.0076	1235	90.4
912				1.56	30.5	13	.0099	1400	93.8
913				1.60	35.5	13	.0115	1495	92.9
914				1.69	41.8	16	.0136	1600	90.8
915	8.2	0.856	164.2	1.71	48.1	22	0.0156	1720	90.8
922	15.0	1.189	124.8	1.38	16.1	54	0.0038	975	87.2
923				1.43	24.2	34	.0057	1115	92.0
924				1.49	32.2	22	.0075	1260	96.3
925				1.57	40.8	21	.0095	1400	97.3
926		1.191	125.0	1.65	48.7	24	0.0114	1505	95.5
927				1.72	56.2	32	.0131	1615	95.5
928		1.193	125.2	1.79	63.9	41	0.0149	1720	95.2
929				1.85	71.0	50	.0165	1820	95.2
930				1.90	77.9	58	.0181	1900	93.9
931				1.99	84.3	69	.0196	2000	95.1
937		1.609	168.9	2.41	19.2	52	0.0033	975	98.8
938				2.47	28.9	39	.0050	1095	98.6
939				2.62	39.6	27	.0068	1240	101.6
940				2.76	49.9	24	.0086	1355	99.9
941				2.87	60.7	37	.0105	1470	98.4
942				3.00	69.7	49	.0120	1575	98.8
943				3.15	83.2	68	.0144	1720	98.4

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TABLE II. - Concluded. OPERATIONAL DATA FOR DIFFERENT DIAMETER LINERS ENCLOSED IN 24-INCH-DIAMETER HOUSING

[Combustor-inlet temperature, 728° R.]

Run	Combustor-inlet static pressure, in. Hg abs	Mass-air-flow rate, lb/sec	Combustor-liner velocity, ft)sec	Static-pressure loss through combustor, in. Hg	Fuel flow, lb/hr	Fuel-atomizer pressure drop, lb/sq in.	Fuel-air ratio	Mean combustor-outlet temperature, °R	Combustion efficiency, percent
				Liner 5					
973	15.0	1.605	168.5	1.34	20.5	26	0.0035	985	96.2
974				1.46	27.4	22	.0047	1075	97.9
975				1.58	37.1	19	.0064	1195	98.4
976				1.63	46.4	21	.0080	1300	97.4
977		1.610	169.0	1.85	55.6	32	0.0096	1415	98.8
978		1.605	168.5	1.99	65.1	43	0.0113	1515	97.5
979		1.606	168.6	2.08	73.7	56	0.0127	1600	96.3
980				2.19	83.2	69	.0144	1690	95.1
1006		0.738	77.5	0.39	19.6	--	0.0074	1220	90.6
1007				.41	24.9	11	.0094	1385	96.6
1008				.43	30.7	10	.0116	1495	92.7
1009				.46	36.8	13	.0138	1610	90.2
1010				.49	40.4	16	.0152	1685	89.7
1011				.51	45.2	20	.0170	1780	89.0
1012				.54	51.1	24	.0192	1895	88.4
1013				.58	56.2	30	.0211	2005	88.9
1014				.63	61.5	37	.0231	2110	88.9
1015				.66	68.8	46	.0259	2240	88.2
1026	8.0	0.396	78.0	0.26	14.5	--	0.0102	1325	80.8
1027				.25	18.4	--	.0129	1520	86.1
1028				.28	22.8	--	.0160	1665	83.6
1029				.32	27.2	--	.0191	1805	81.9
1030				.34	31.4	--	.0220	1925	79.9
1031				.37	35.8	--	.0251	2050	78.6
1032				.40	40.8	--	.0286	2185	77.3
1033				.41	44.3	16	.0311	2260	75.6
1034		0.858	168.8	0.90	22.6	--	0.0073	1200	87.5
1035				.96	27.7	--	.0090	1335	92.9
1036				1.05	33.0	--	.0107	1425	90.5
1037				1.12	38.4	--	.0124	1520	89.3
1038				1.18	44.4	19	.0144	1615	87.4
1039	8.2	0.858	164.7	1.26	52.6	27	0.0170	1750	86.2
1053	5.0	0.255	80.3	0.15	11.3	--	0.0123	1390	74.8
1054				.20	14.8	--	.0161	1560	73.2
1055				.21	18.1	--	.0197	1740	74.3
1056				.24	22.3	--	.0243	1895	71.0
1057				.26	26.0	--	.0283	1980	66.3
1058				.29	29.5	--	.0321	2140	67.1
1059		0.397	125.0	0.41	15.8	--	0.0111	1450	90.8
1060				.43	21.2	--	.0148	1555	78.8
1061	5.1	0.397	122.6	----	23.8	--	0.0167	1640	78.1
				Liner 6					
944	15.0	1.606	168.7	2.78	50.2	--	0.0087	1350	98.3
945				2.93	58.7	--	.0101	1460	100.1
946				3.02	71.0	--	.0123	1585	98.1
947				3.14	81.7	--	.0141	1695	97.3
948	15.4	1.610	164.5	3.20	94.2	13	0.0162	1820	96.7
				Liner 7					
958	15.0	1.605	168.5	1.67	46.4	--	0.0080	1265	91.2
959				1.82	55.0	--	.0095	1400	97.4
960				1.95	63.5	--	.0110	1485	95.9
961				2.04	70.5	--	.0122	1565	96.3
962				2.19	83.5	--	.0144	1695	95.2
963	15.4	1.605	164.0	2.24	92.1	12	0.0159	1775	94.2

TABLE III. - OPERATIONAL DATA FOR DIFFERENT DIAMETER LINERS ENCLOSED IN 7.0-INCH-DIAMETER HOUSING

[Combustor-inlet temperature, 726° R.]

Run	Combustor-inlet total pressure, in. Hg abs	Mass-air-flow rate, lb/sec	Combustor-liner velocity, ft/sec	Combustor reference velocity, ft/sec	Total-pressure loss through combustor, in. Hg	Fuel flow, lb/hr	Fuel-atomizer pressure drop, lb/sq in.	Fuel-air ratio	Mean combustor-outlet temperature, °R	Combustion efficiency, percent
					Liner 1 (with air-guide tubes)					
247	15.0	0.572	170.3	78.5	0.68	16.9	13.8	0.0082	1240	85.0
248					.71	22.6	15.3	.0110	1400	84.8
249					.73	29.6	15.3	.0144	1507	76.2
250		0.571	170.0	78.3	0.76	36.1	17.3	0.0176	1694	78.9
251					.79	42.2	21.5	.0205	1854	80.0
252					.82	46.8	25.8	.0228	1965	80.3
253					.85	51.2	31.1	.0249	2066	80.2
254					.87	54.8	36.3	.0266	2151	80.4
255					.89	59.8	43.1	.0291	2248	79.6
256					.90	63.0	49.5	.0306	2328	90.2
257					.93	66.2	55.3	.0322	2392	79.9
258					1.00	70.0	----	.0340	2450	78.8
260		0.742	221.0	101.7	1.12	22.4	17.8	0.0064	1187	74.4
261					1.19	30.1	18.3	.0113	1358	77.3
262					1.23	35.3	19.5	.0132	1486	80.3
263					1.28	40.6	21.8	.0152	1607	82.0
264					1.31	45.7	25.3	.0171	1714	82.7
265					1.34	50.7	30.8	.0190	1815	83.0
266					1.38	55.9	38.3	.0209	1915	83.1
267					1.43	61.5	46.8	.0230	2017	82.9
268					1.46	66.7	56.4	.0250	2114	83.1
269					1.51	71.5	65.3	.0268	2195	82.8
270					1.54	76.0	73.6	.0284	2263	82.1
271					1.55	80.6	83.3	.0302	2335	81.7
273	8.0	0.397	221.5	102.0	0.64	21.8	18.5	0.0153	1187	41.3
285	15.0	1.188	353.5	163.0	3.26	40.8	21.1	0.0095	1300	82.3
286					3.40	48.7	28.1	.0114	1405	82.5
287					3.48	54.3	35.3	.0127	1475	92.3
					Liner 1 (without air-guide tubes)					
296	15.0	1.184	352.6	162.4	2.88	31.6	8.8	0.0074	1085	65.0
297					2.96	36.8	13.3	.0086	1185	72.1
298					3.10	42.2	18.8	.0099	1268	74.8
299					3.11	43.7	20.3	.0102	1315	78.8
300		0.571	170.0	78.3	0.60	20.3	----	0.0099	1150	58.3
301					.62	25.7	----	.0125	1351	69.2
302					.66	30.3	8.3	.0147	1507	74.5
303					.70	36.2	12.8	.0176	1683	77.8
304					.73	40.1	18.1	.0195	1795	79.4
305					.76	45.2	24.1	.0220	1925	80.1
306					.79	50.9	30.8	.0248	2062	80.4
307					.82	56.7	38.5	.0276	2000	69.1
308		0.572	170.3	78.5	0.77	61.2	45.8	0.0297	1910	59.6
309		0.742	221.0	101.7	1.01	21.2	----	0.0079	1102	63.8
310					1.07	28.6	7.6	.0107	1312	75.2
311					1.12	33.8	10.8	.0126	1440	78.6
312					1.16	38.7	15.8	.0145	1570	82.1
313					1.20	43.1	21.2	.0161	1667	83.0
314					1.25	48.4	27.3	.0181	1770	83.0
315					1.29	54.1	35.3	.0202	1890	83.1
316					1.36	59.8	43.8	.0224	1982	82.7
317					1.32	64.1	51.0	.0240	1675	57.5
318					----	66.9	56.5	.0250	1510	45.2
319	8.0	0.397	221.7	102.0	0.57	19.7	----	0.0138	1115	38.7
320					.58	24.1	----	.0169	1170	36.8
321					----	29.1	----	.0204	1260	36.9
					Liner 2 (with air-guide tubes)					
323	15.0	0.573	124.2	78.6	1.24	28.6	25.3	0.0139	1510	79.3
324					1.27	34.1	22.8	.0165	1675	81.9
325					1.28	38.7	23.3	.0188	1804	83.1
326					1.32	43.6	25.3	.0211	1947	84.7
327					1.33	47.9	28.3	.0232	2062	85.4
328					1.37	53.8	34.3	.0261	2218	86.2
329					1.38	58.7	41.3	.0284	2311	84.9
330					1.40	63.0	48.5	.0305	2407	84.7
331					1.42	67.2	56.3	.0326	2500	84.6
332					1.23	26.6	19.8	.0129	1460	79.4
333		0.742	160.8	101.7	2.16	33.8	27.3	0.0126	1482	83.4
334					2.18	39.7	27.3	.0149	1625	85.6
335					2.21	45.4	29.3	.0170	1770	88.2
336					2.26	53.2	33.3	.0199	1945	89.4
337					2.29	59.8	43.4	.0224	2078	89.5
338					2.34	66.2	55.3	.0248	2205	89.8
339					2.39	73.4	68.3	.0275	2327	88.6

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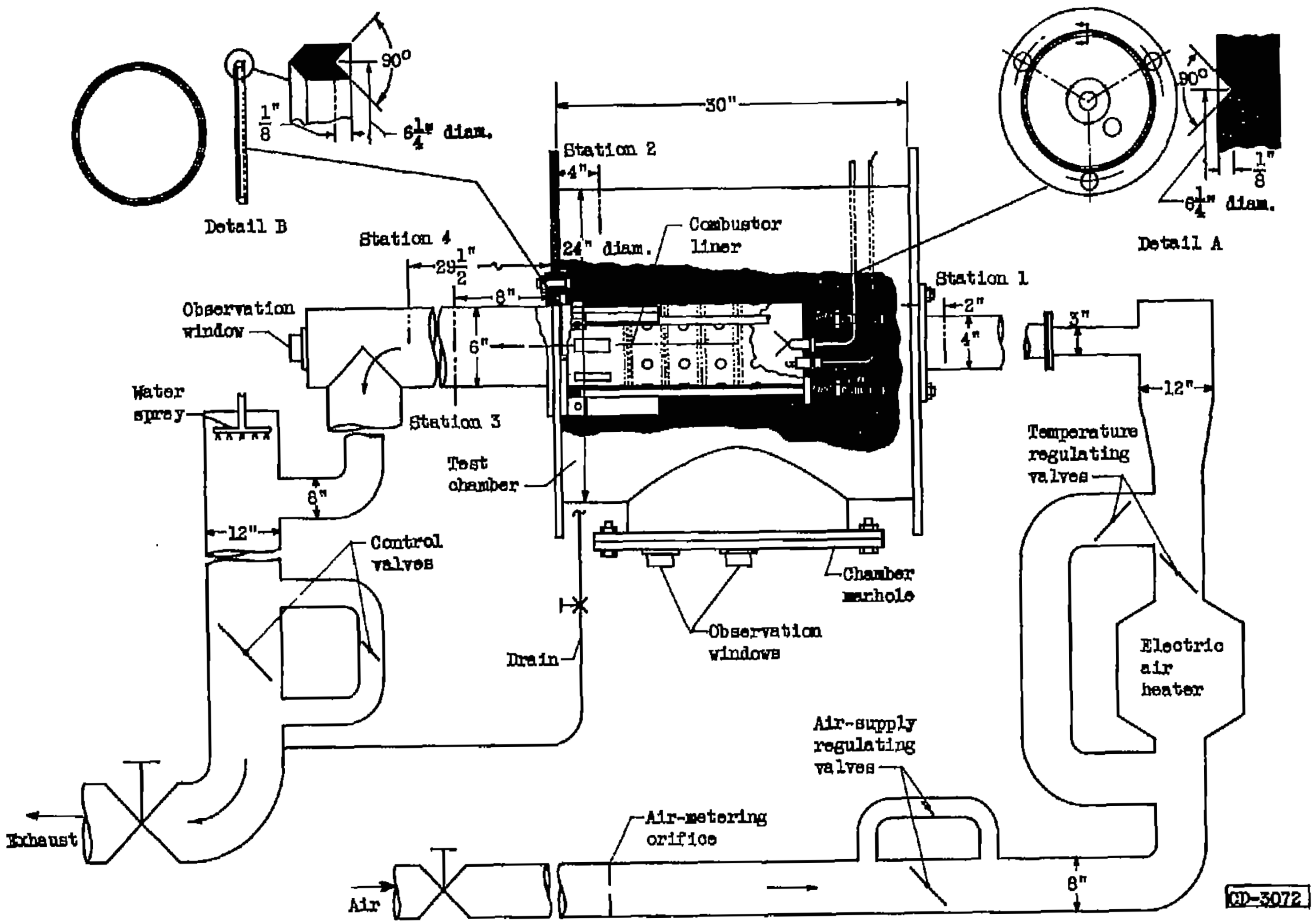
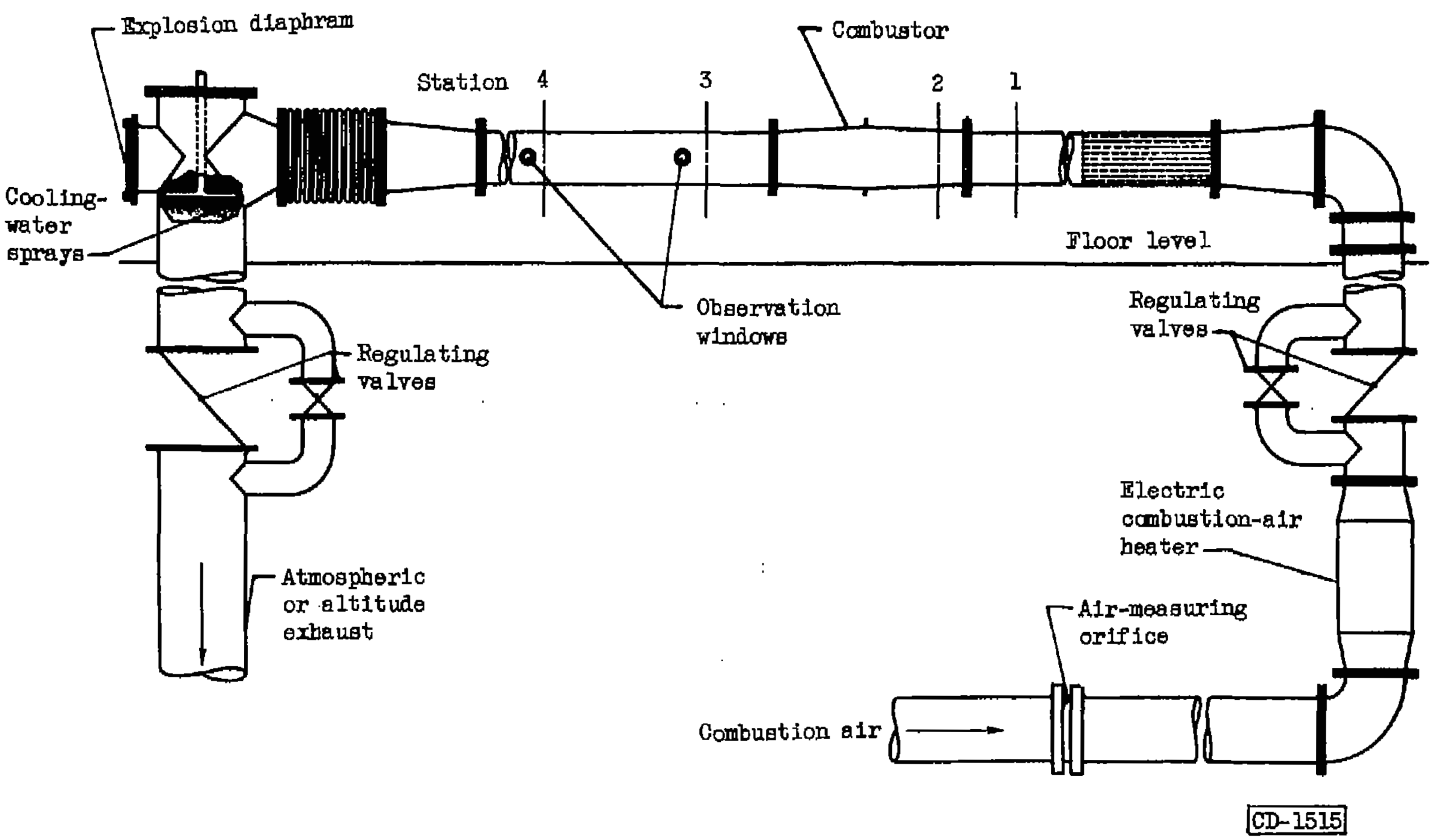


(a) 24-Inch-diameter combustor housing (showing details of chamber and combustor assembly).

Figure 1. - Diagrams of test installations.



(b) 7-Inch-diameter combustor housing.

Figure 1. - Concluded. Diagrams of test installations.

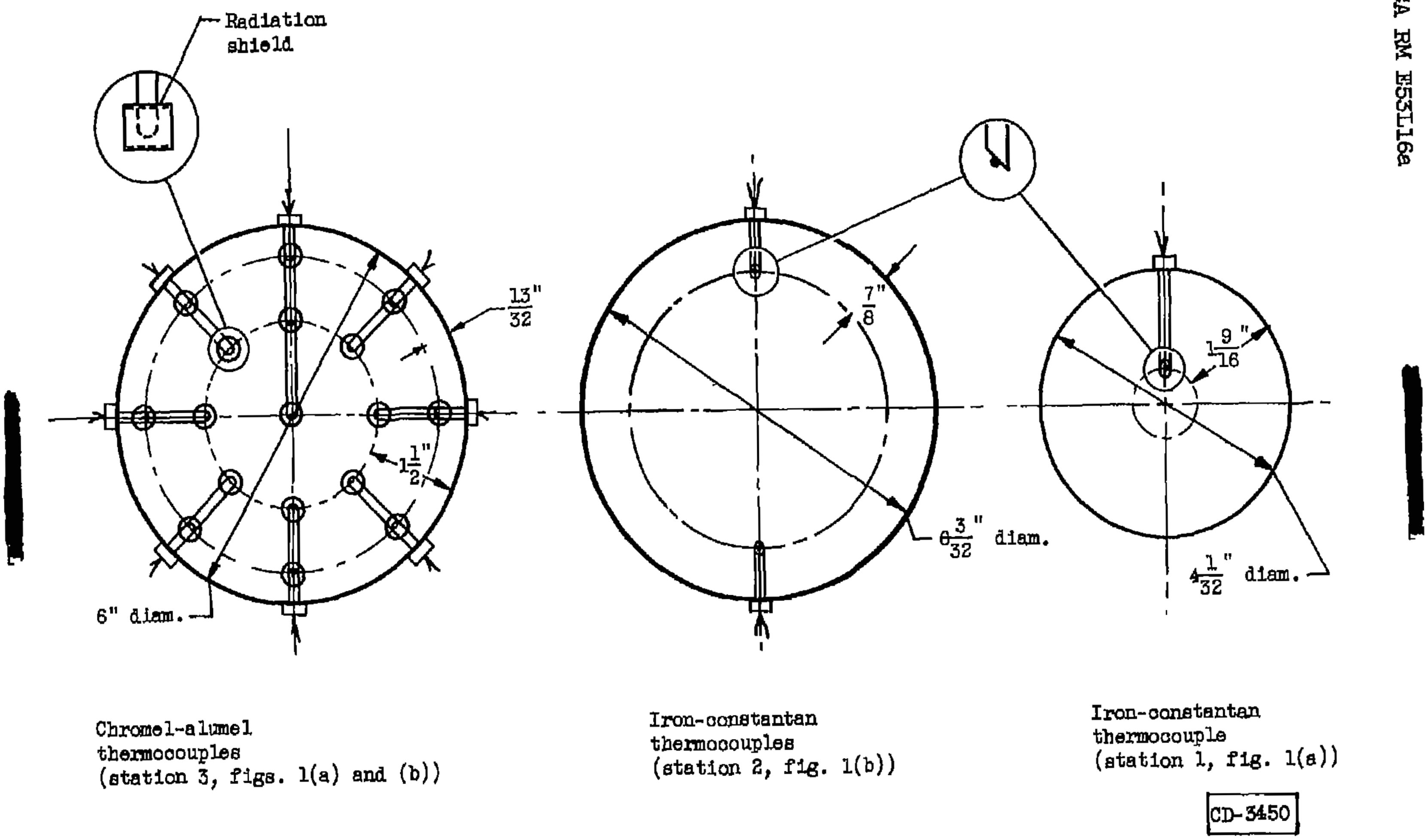


Figure 2. - Sketch showing arrangement of thermocouples at various stations.

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Liner \ Position		A	B	C	D	E	F
1	No. holes	6	255	6	6	144	68
	Size, in.	1×2	$\frac{1}{16}$ diam.	$\frac{5}{8}$ diam.	0.605 I.D.	$\frac{1}{16}$ diam.	$\frac{1}{16}$ diam.
2	No. holes	6	285	6	6	168	75
	Size, in.	1×2	$\frac{1}{16}$ diam.	$\frac{11}{16}$ diam.	0.680 I.D.	$\frac{1}{16}$ diam.	$\frac{1}{16}$ diam.
3	No. holes	6	315	6	6	189	126
	Size, in.	1×2	$\frac{1}{16}$ diam.	$\frac{5}{8}$ diam.	0.605 I.D.	$\frac{1}{16}$ diam.	$\frac{1}{16}$ diam.
4,6	No. holes	6	240	6	6	160	75
	Size, in.	1×2	$\frac{1}{16}$ diam.	$\frac{5}{8}$ diam.	0.605 I.D.	$\frac{1}{16}$ diam.	$\frac{1}{16}$ diam.
5,7	No. holes	6	520	6	6	340	162
	Size, in.	$1\frac{1}{2}$×3	$\frac{1}{16}$ diam.	$\frac{15}{16}$ diam.	0.930 I.D.	$\frac{1}{16}$ diam.	$\frac{1}{16}$ diam.

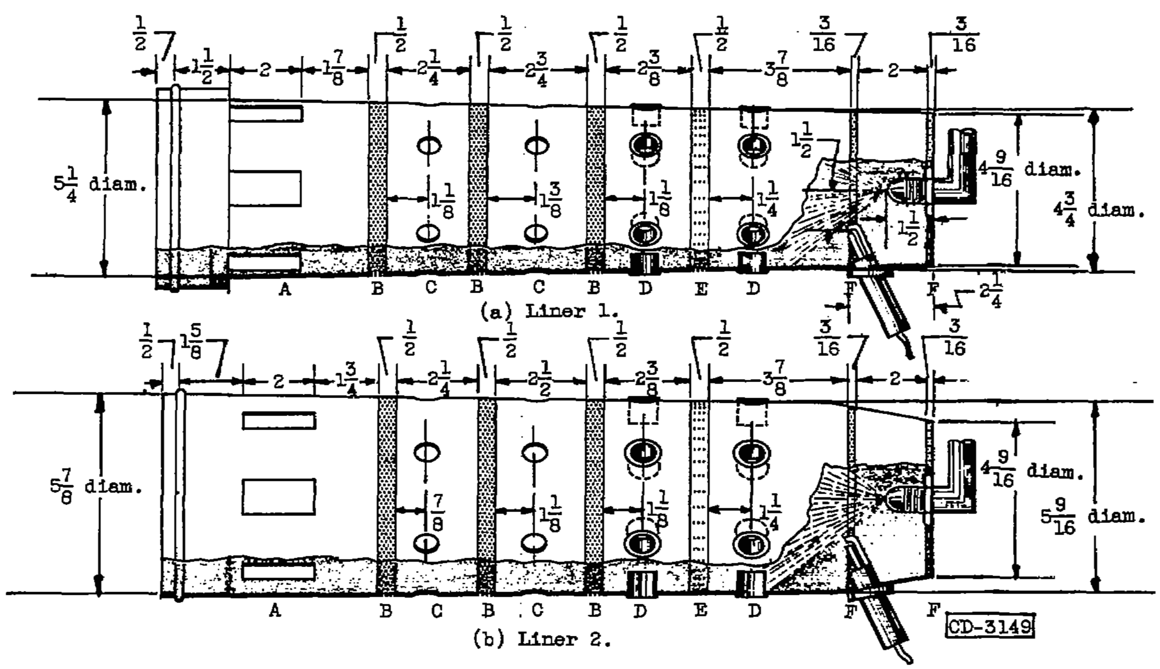
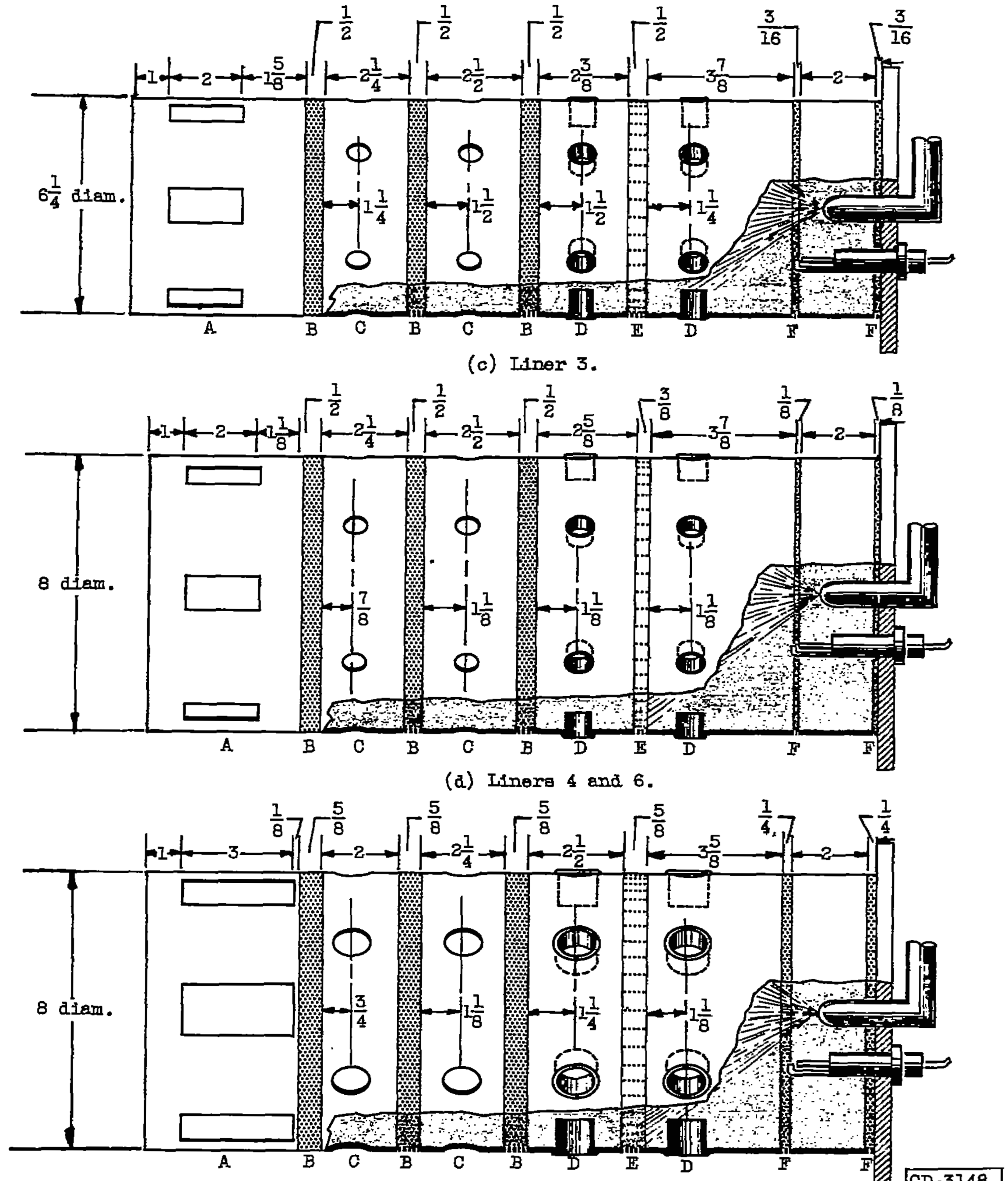


Figure 3. - Sketches of various experimental combustor liners showing design details. (All dimensions in inches.)

3029

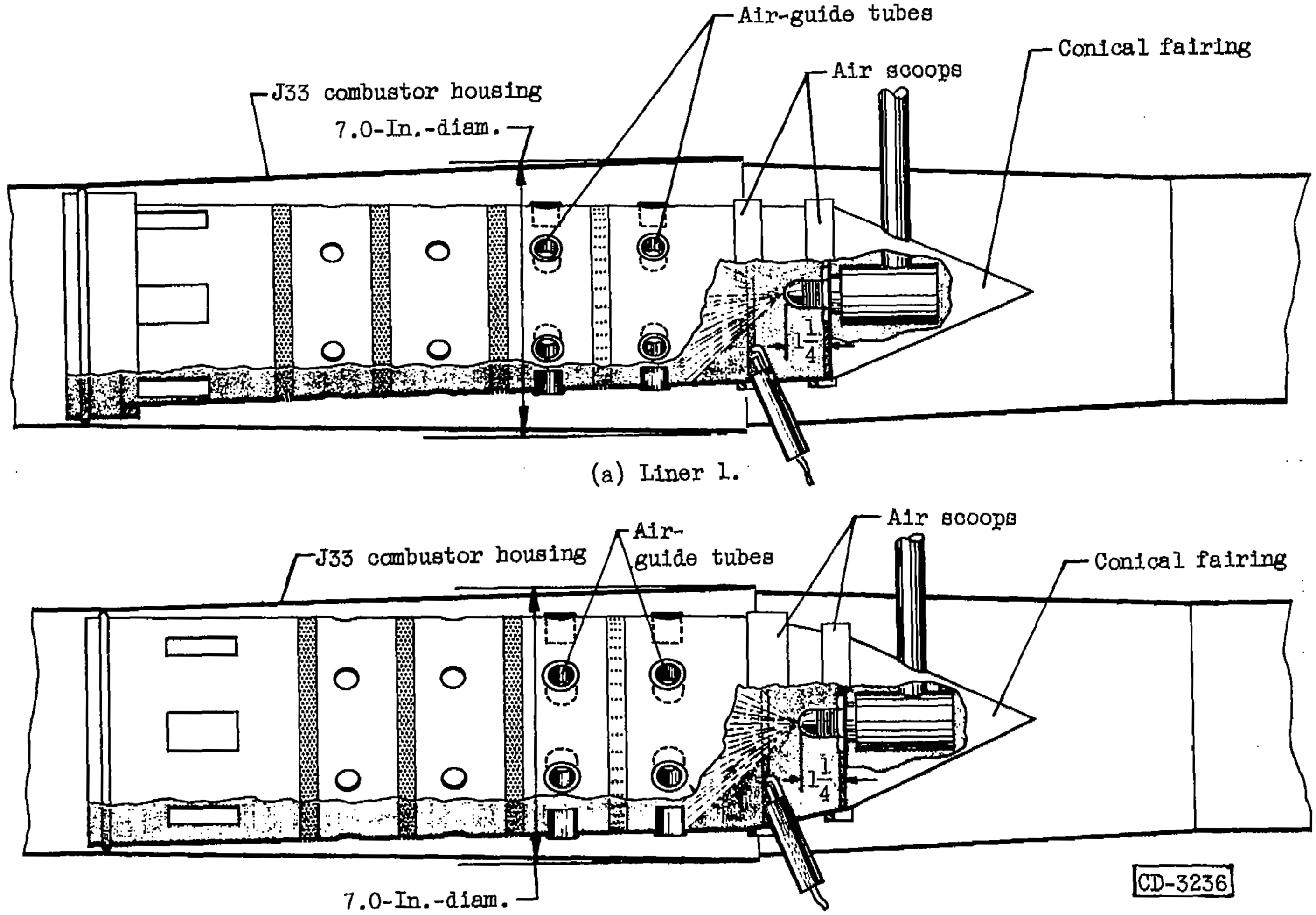


(c) Liner 3.

(d) Liners 4 and 6.

(e) Liners 5 and 7.

Figure 3. - Concluded. Sketches of various experimental combustor liners showing design details. (All dimensions in inches.)



(a) Liner 1.

(b) Liner 2.

Figure 4. - Sketches showing combustor liners 1 and 2 installed in a 7-inch-diameter (J33) combustor housing.

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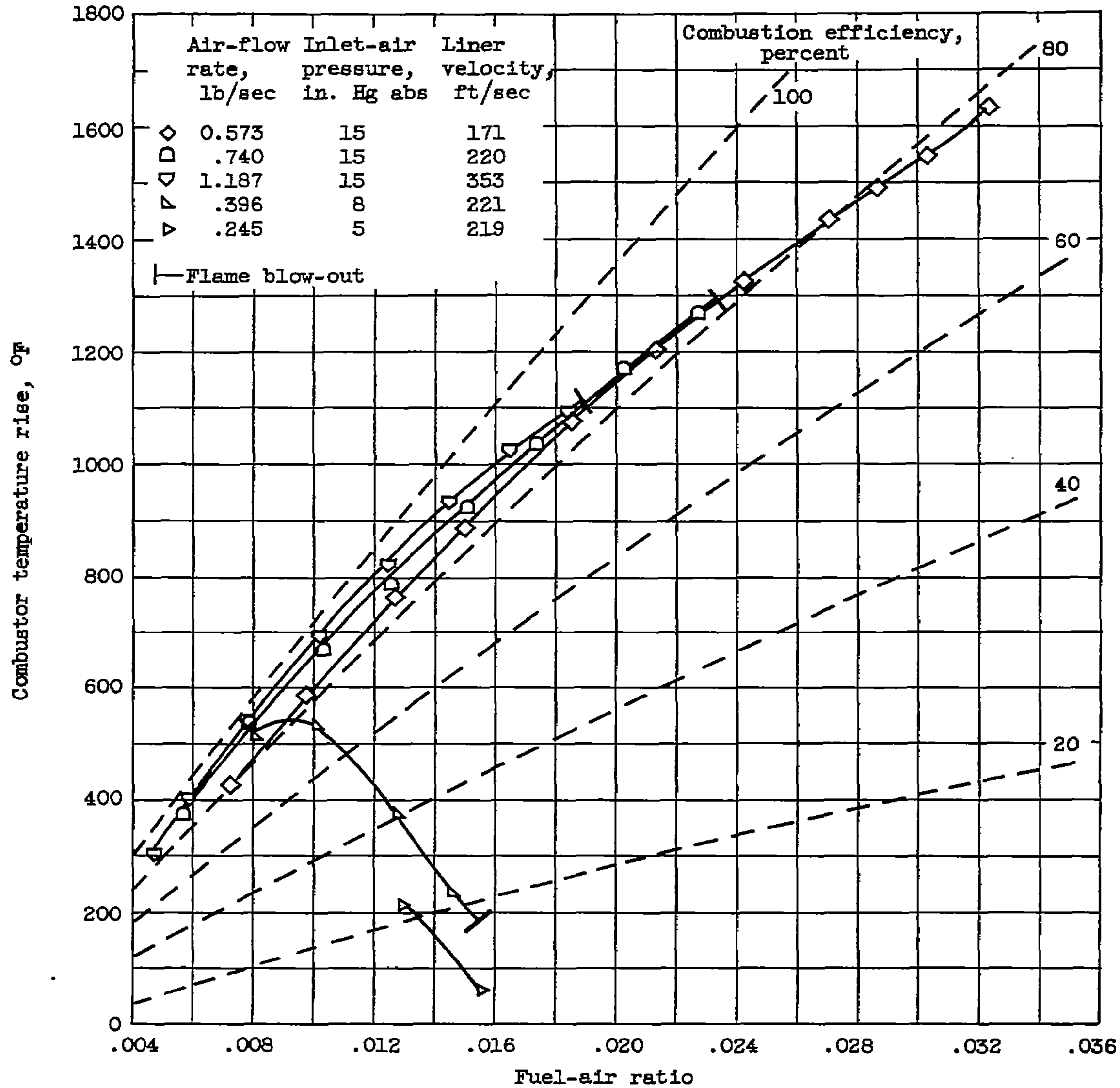
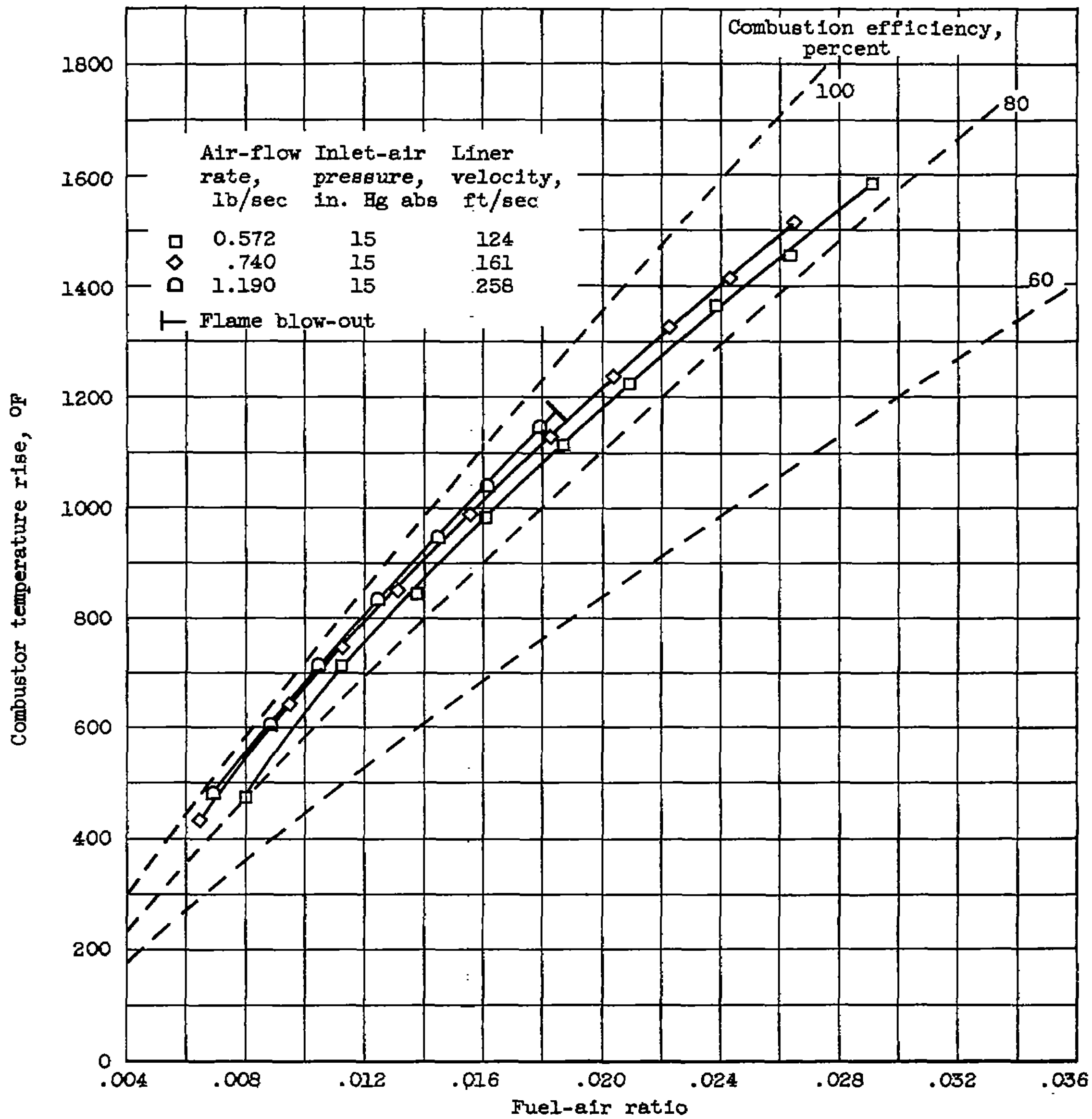


(a) Liner 1.

Figure 5. - Combustor temperature-rise data obtained with various liners installed in 24-inch-diameter housing at various inlet-air pressure and velocity conditions. Inlet-air temperature, 268° F.

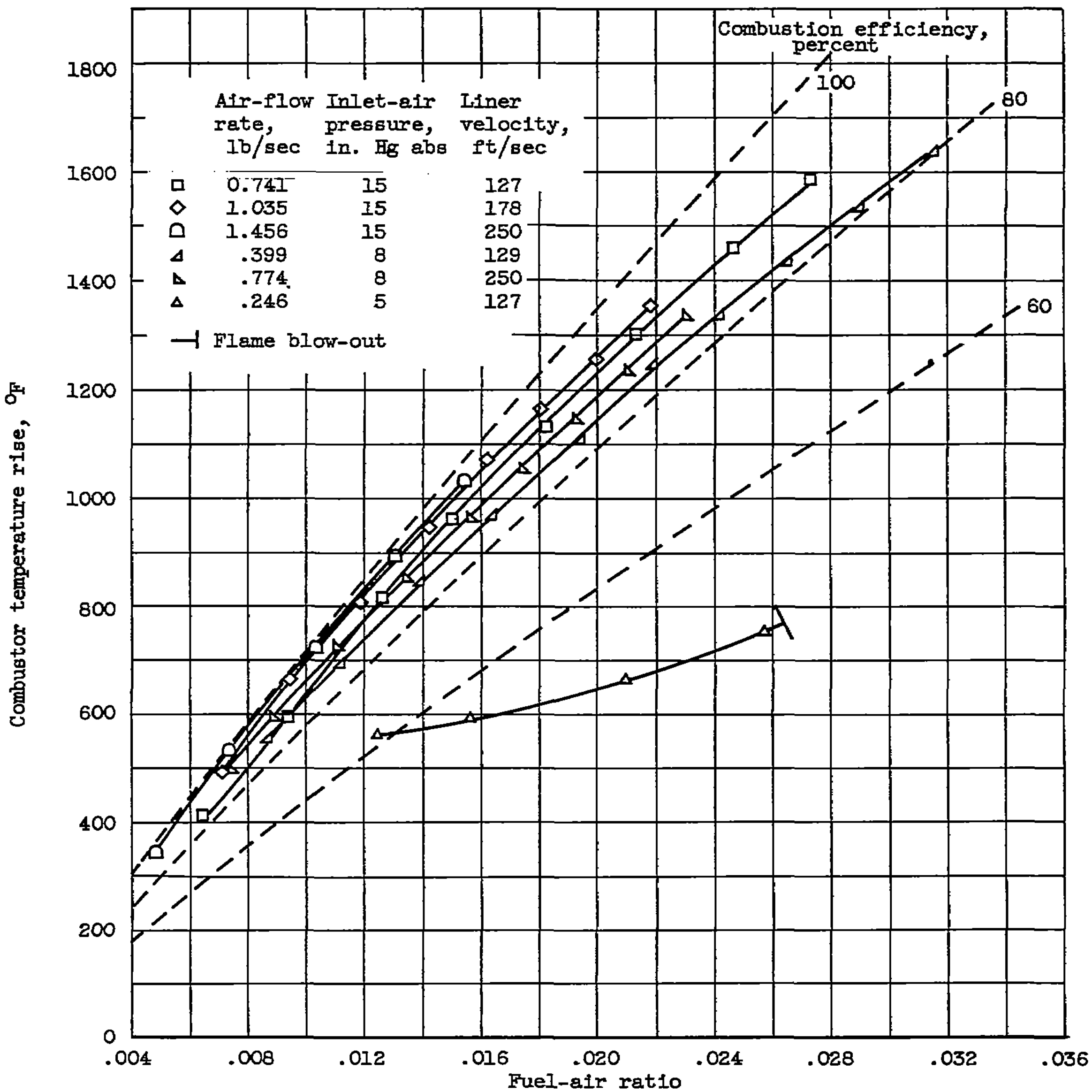
3029



(b) Liner 2.

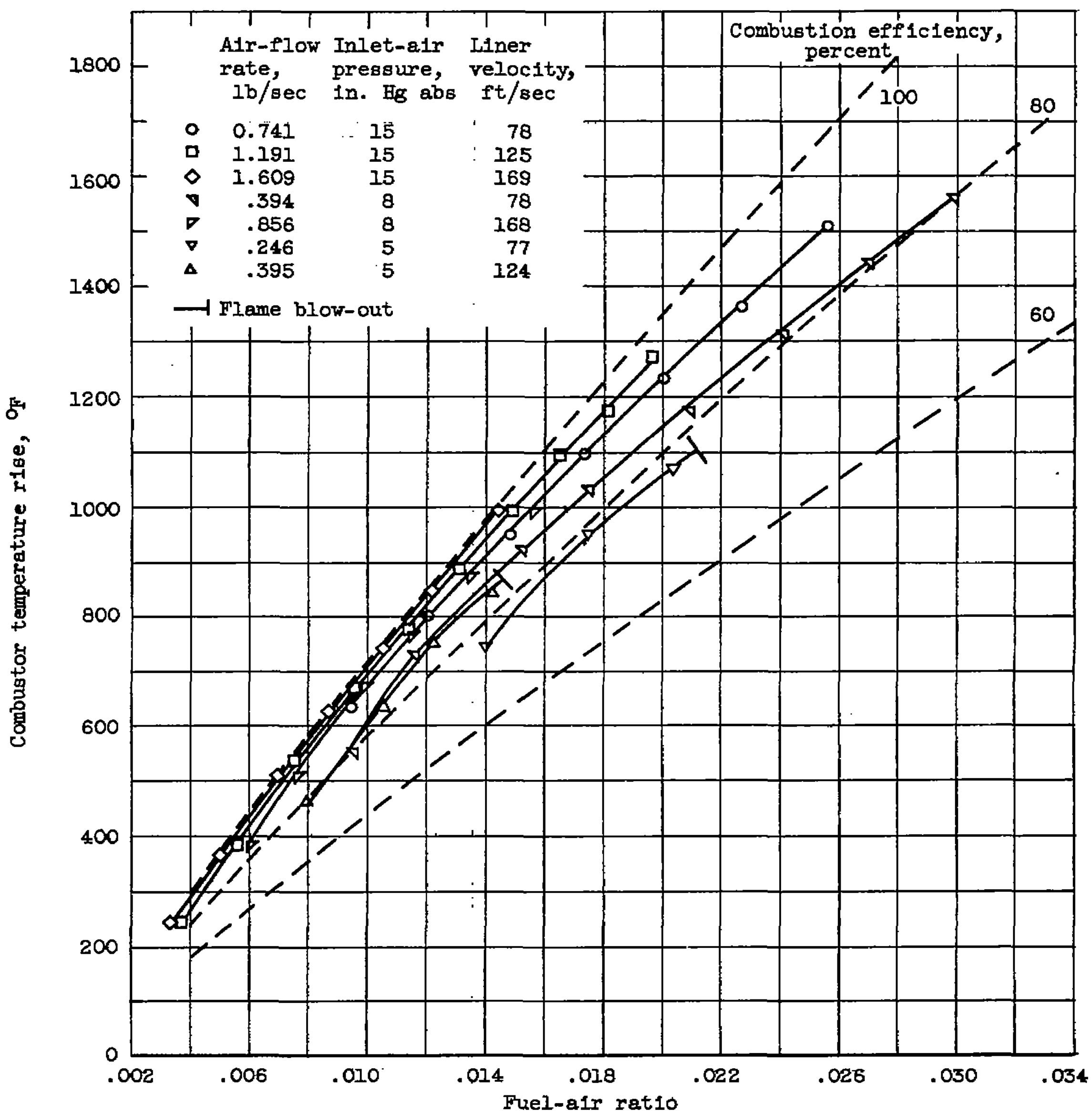
Figure 5. - Continued. Combustor temperature-rise data obtained with various liners installed in 24-inch-diameter housing at various inlet-air pressure and velocity conditions. Inlet-air temperature, 268° F.

3029



(c) Liner 3.

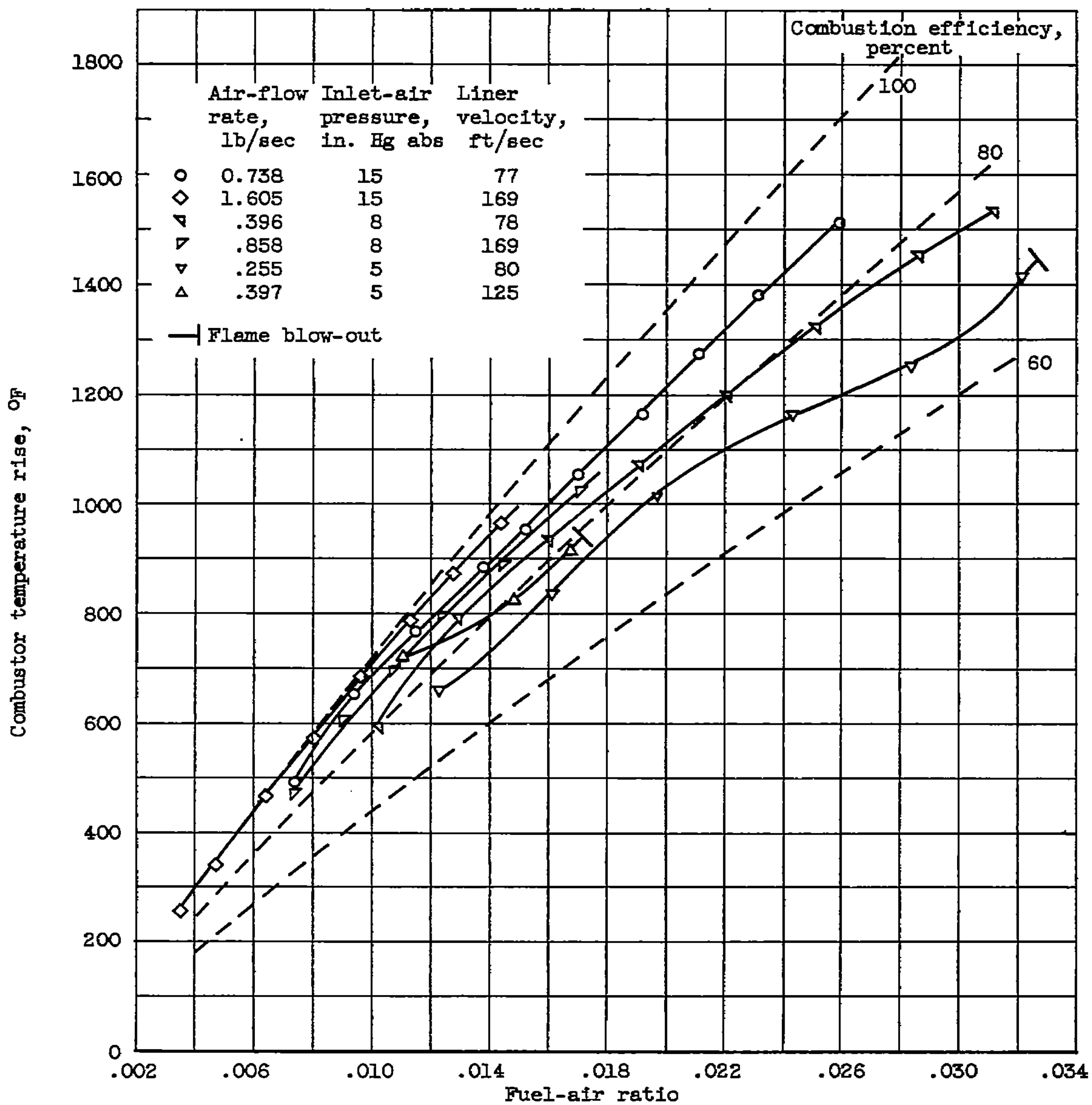
Figure 5. - Continued. Combustor temperature-rise data obtained with various liners installed in 24-inch-diameter housing at various inlet-air pressure and velocity conditions. Inlet-air temperature, 268° F.



(d) Liner 4.

Figure 5. - Continued. Combustor temperature-rise data obtained with various liners installed in 24-inch-diameter housing at various inlet-air pressure and velocity conditions. Inlet-air temperature, 268° F.

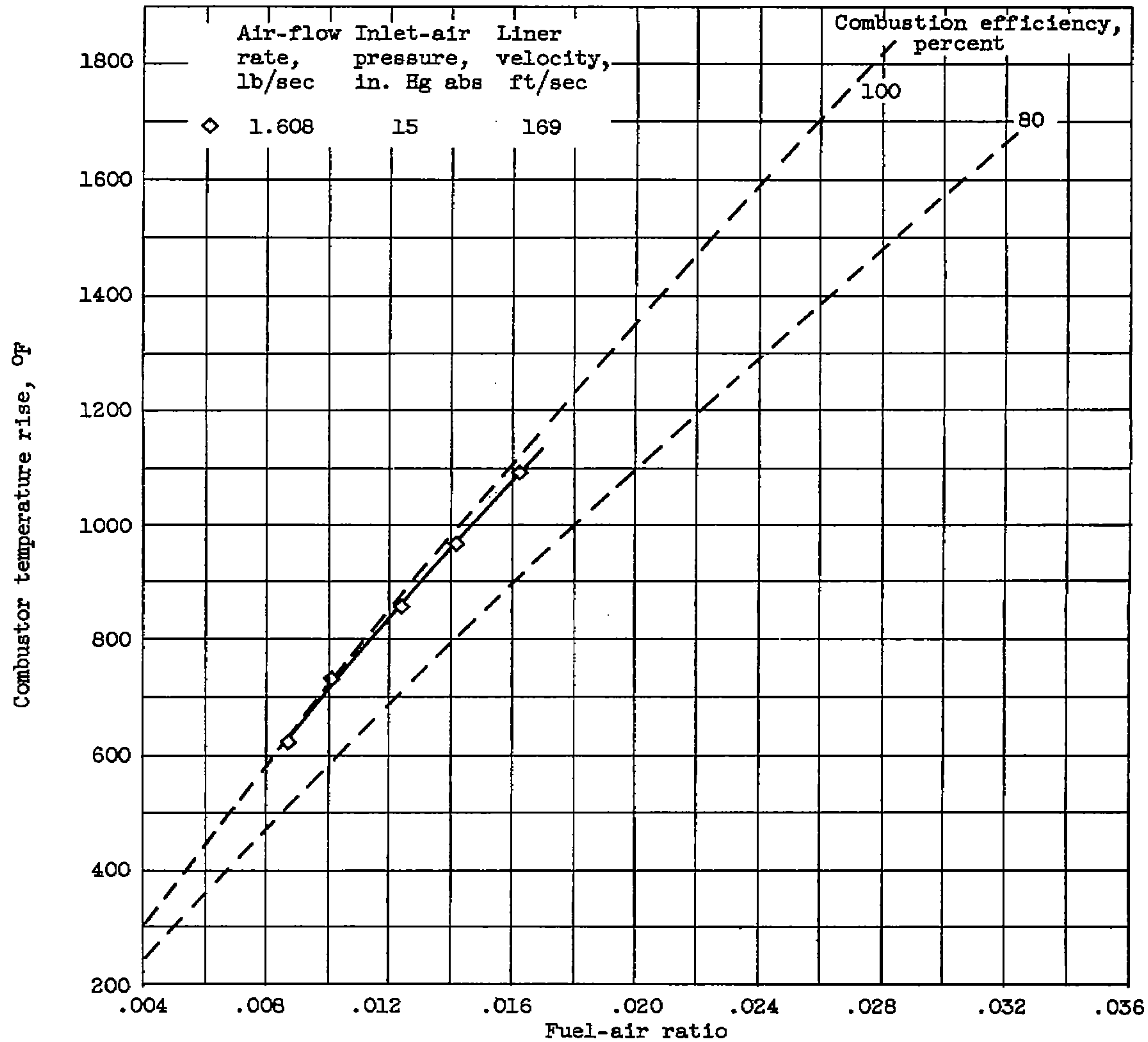
3029



(e) Liner 5.

Figure 5. - Continued. Combustor temperature-rise data obtained with various liners installed in 24-inch-diameter housing at various inlet-air pressure and velocity conditions. Inlet-air temperature, 268° F.

3029



(f) Liner 6.

Figure 5. - Continued. Combustor temperature-rise data obtained with various liners installed in 24-inch-diameter housing at various inlet-air pressure and velocity conditions. Inlet-air temperature, 268° F.

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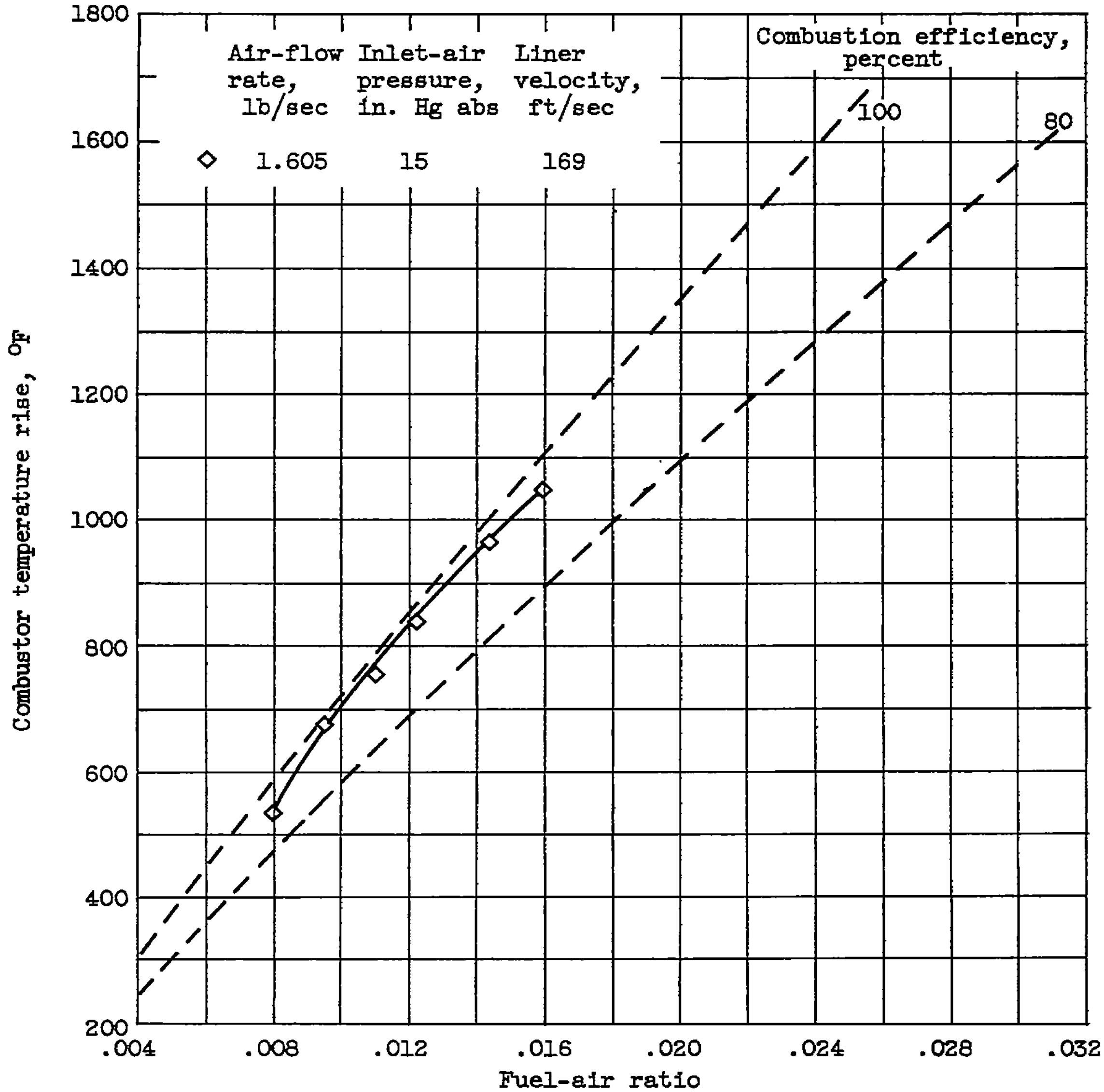

(g) Liner 7.

Figure 5. - Concluded. Combustor temperature-rise data obtained with various liners installed in 24-inch-diameter housing at various inlet-air pressure and velocity conditions. Inlet-air temperature, 268° F.

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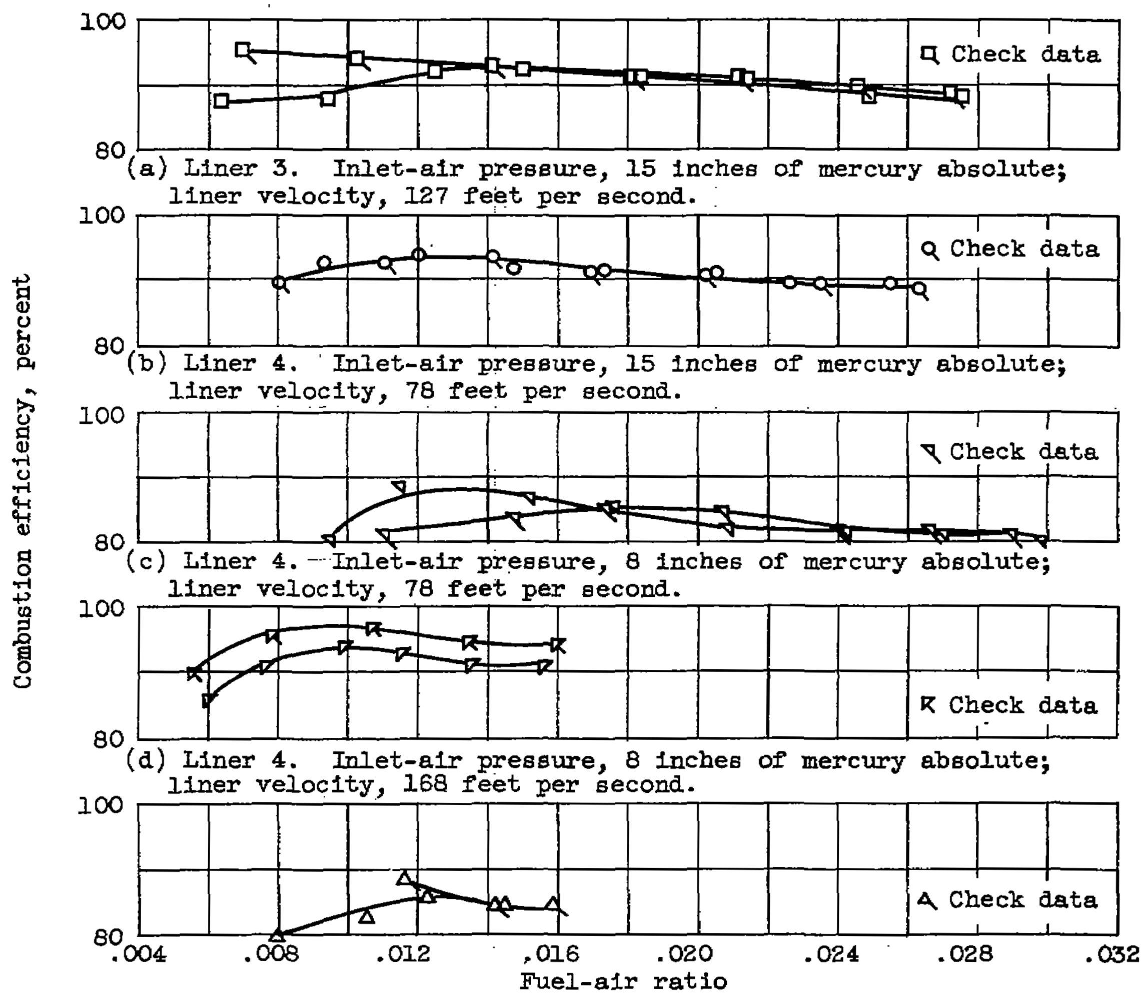


(a) Liner 3. Inlet-air pressure, 15 inches of mercury absolute; liner velocity, 127 feet per second.

(b) Liner 4. Inlet-air pressure, 15 inches of mercury absolute; liner velocity, 78 feet per second.

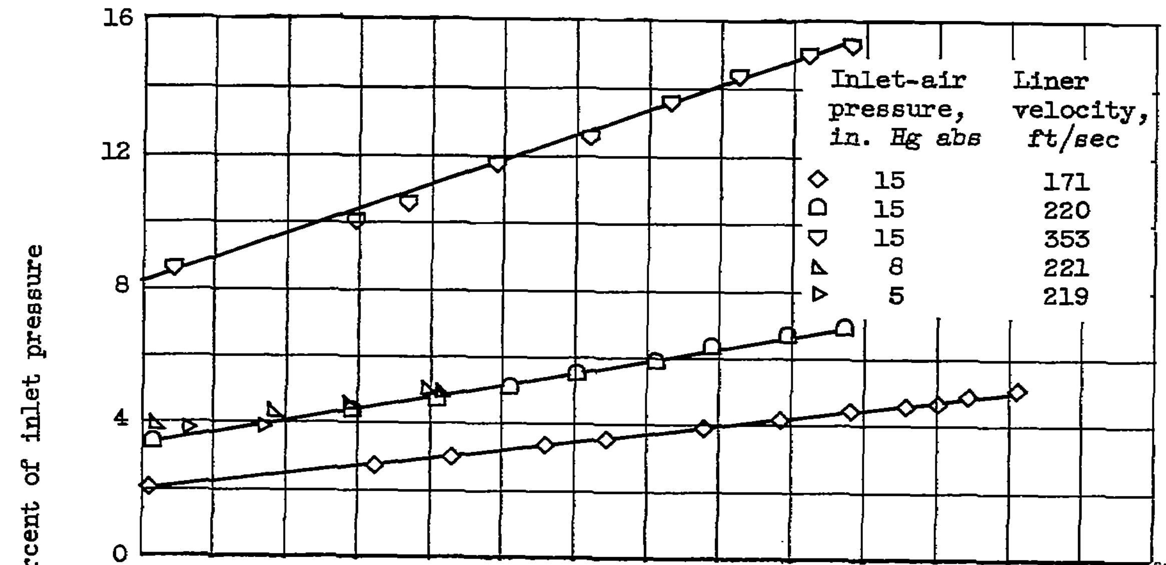
(c) Liner 4. Inlet-air pressure, 8 inches of mercury absolute; liner velocity, 78 feet per second.

(d) Liner 4. Inlet-air pressure, 8 inches of mercury absolute; liner velocity, 168 feet per second.

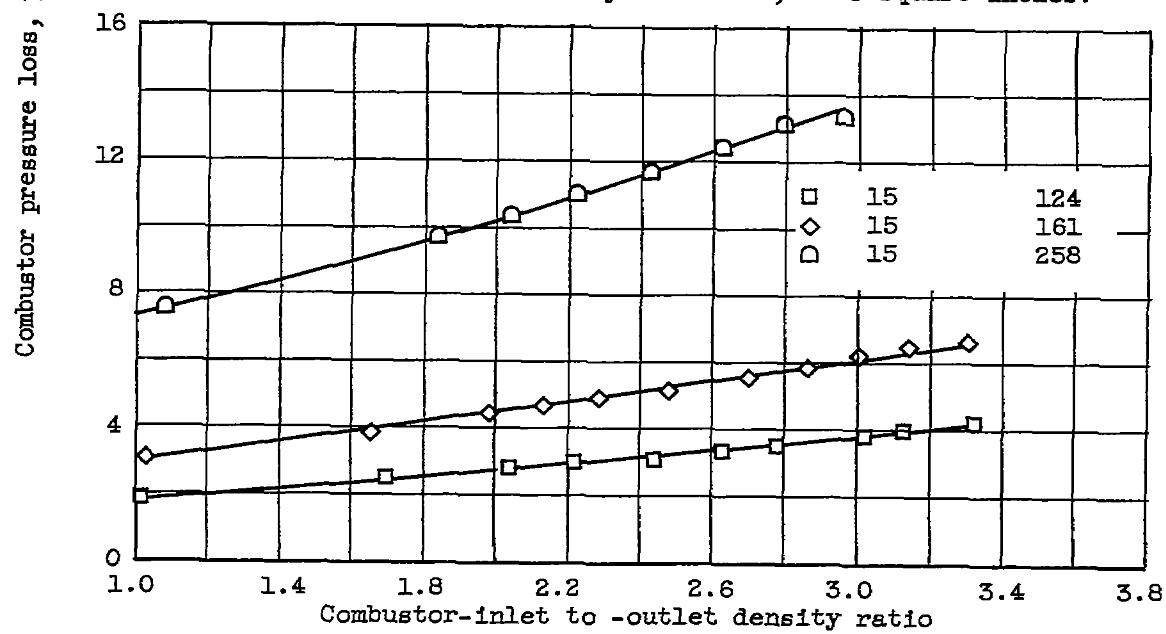
(e) Liner 4. Inlet-air pressure, 5 inches of mercury absolute; liner velocity, 124 feet per second.

Figure 6. - Reproducibility of combustion-efficiency data obtained with two combustor liners installed in 24-inch-diameter housing at various inlet-air pressure and velocity conditions. Inlet-air temperature, 268° F.

3029



(a) Liner 1. Total air-entry-hole area, 22.3 square inches.



(b) Liner 2. Total air-entry-hole area, 24.4 square inches.

Figure 7. - Combustor pressure-loss data obtained with various liners installed in 24-inch-diameter housing at various inlet-air pressure and velocity conditions. Inlet-air temperature, 268° F.

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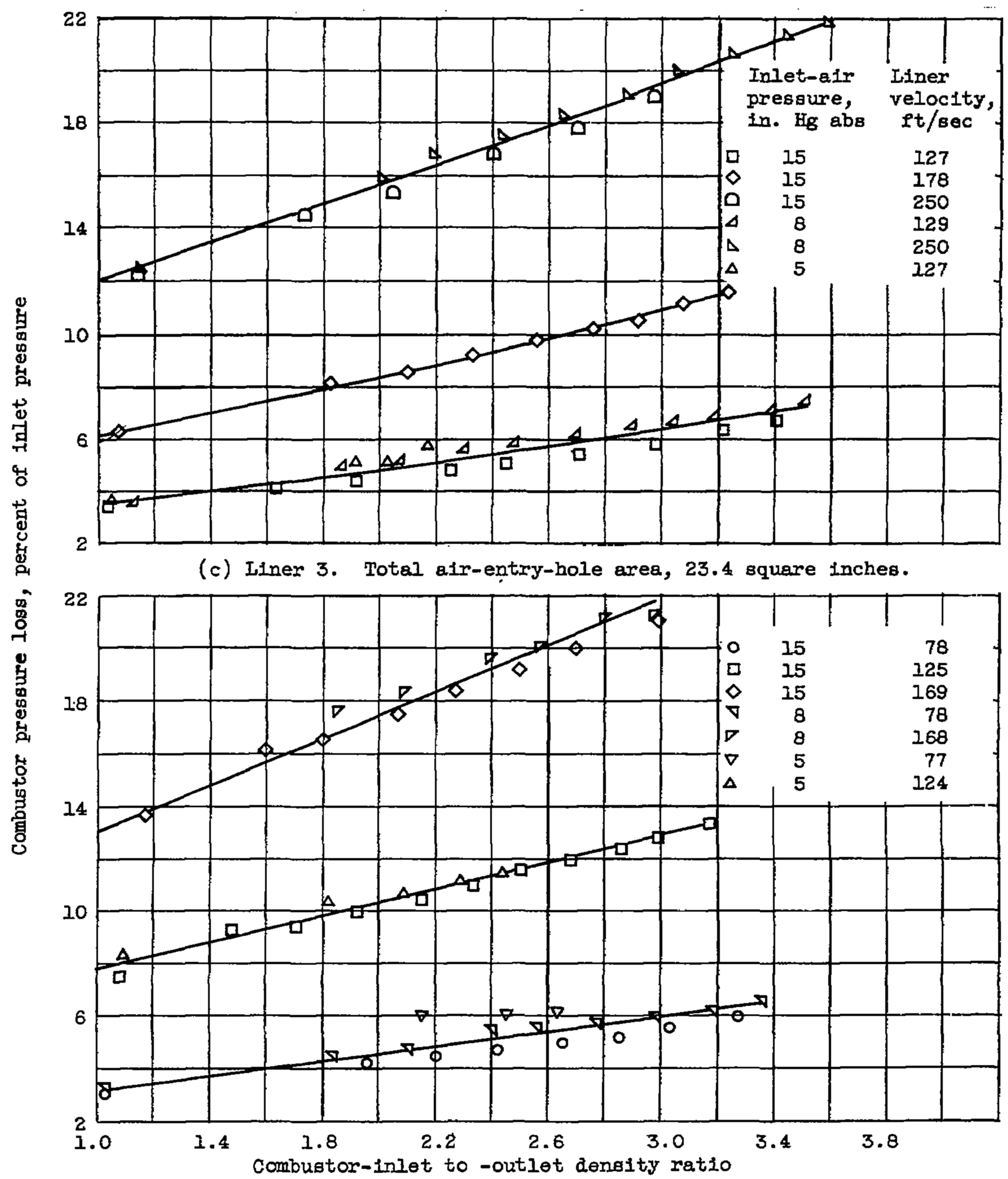
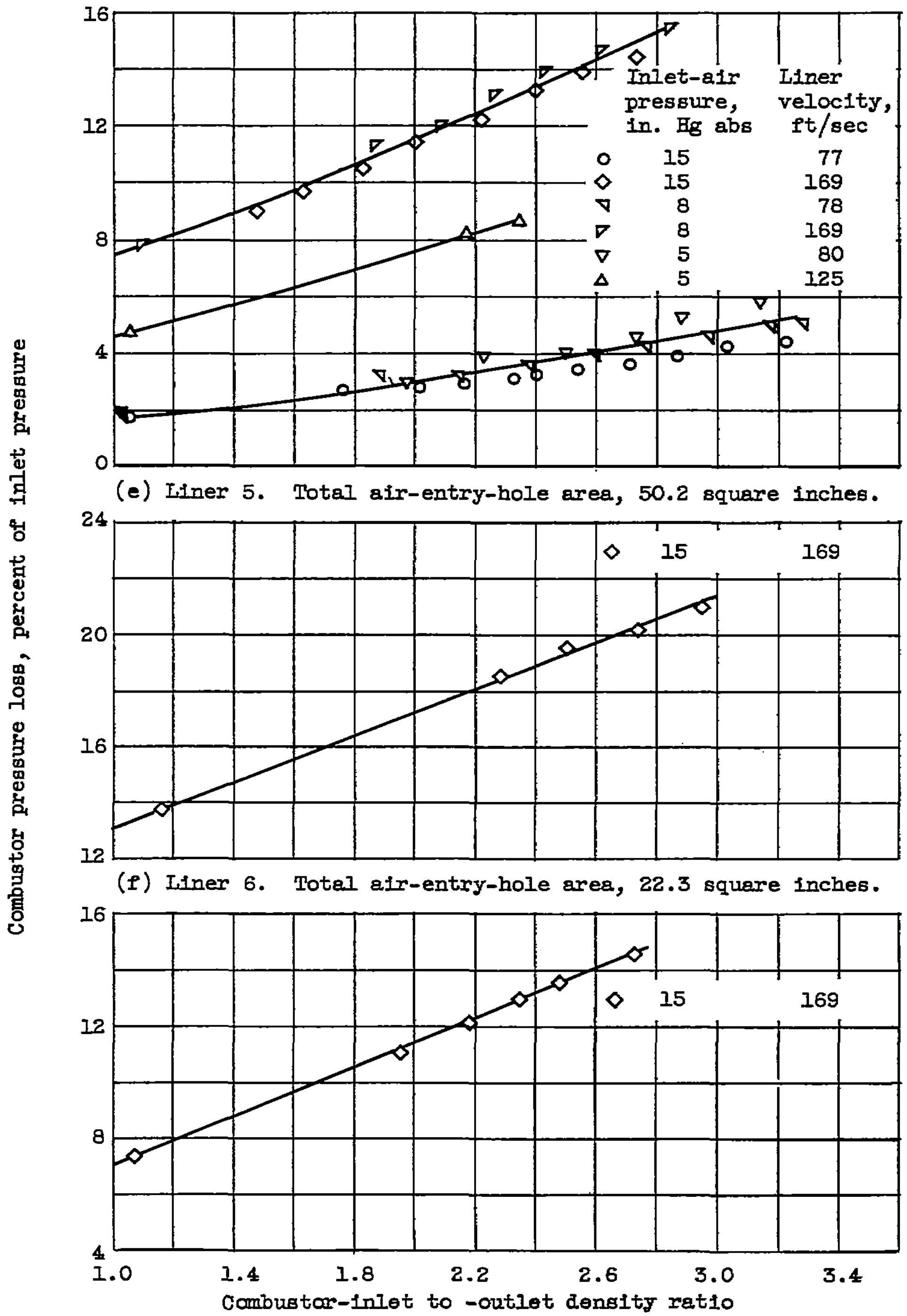


(c) Liner 3. Total air-entry-hole area, 23.4 square inches.

(d) Liner 4. Total air-entry-hole area, 22.3 square inches.

Figure 7. - Continued. Combustor pressure-loss data obtained with various liners installed in 24-inch-diameter housing at various inlet-air pressure and velocity conditions. Inlet-air temperature, 268° F.

3029



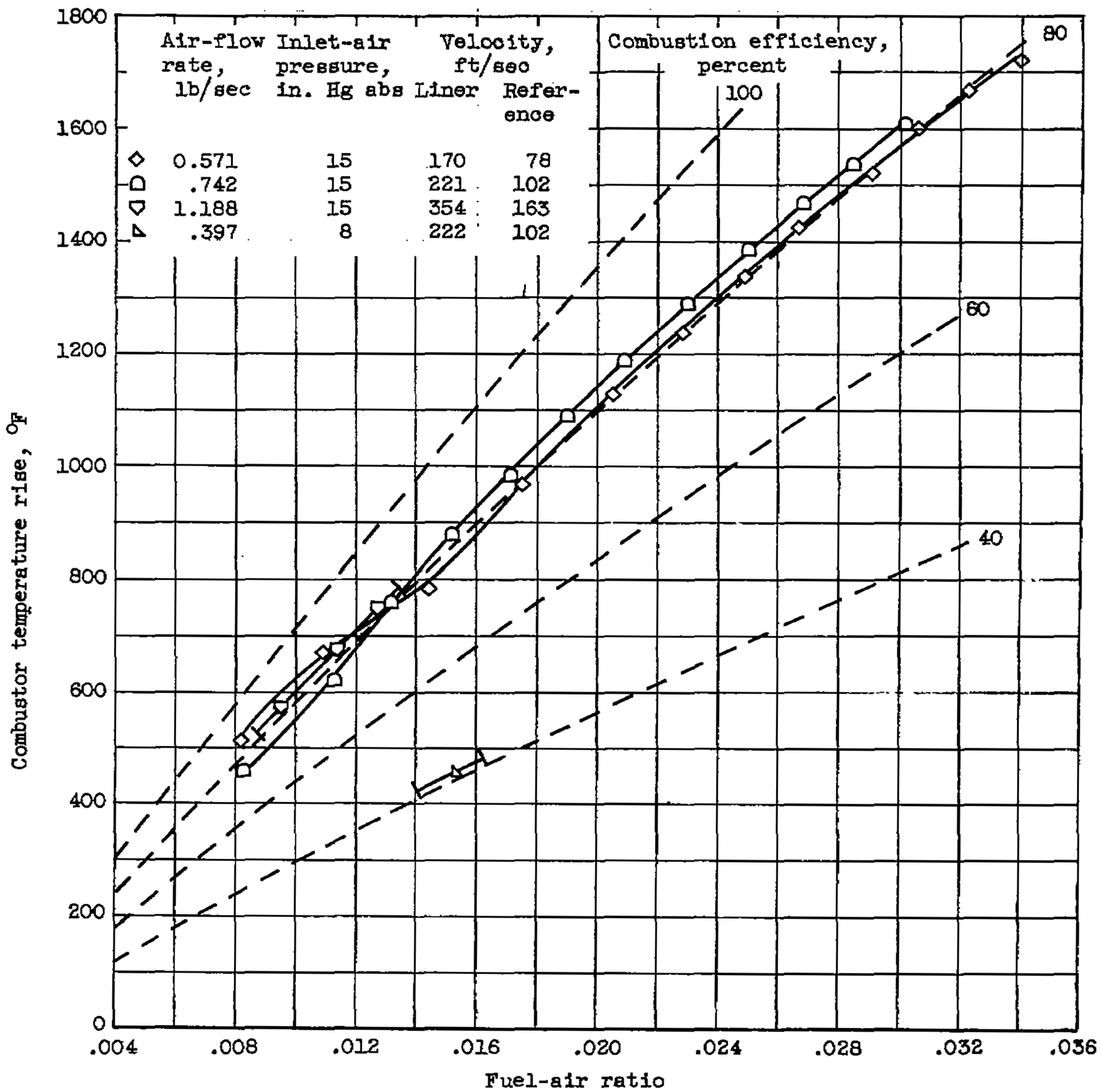
(e) Liner 5. Total air-entry-hole area, 50.2 square inches.

(f) Liner 6. Total air-entry-hole area, 22.3 square inches.

(g) Liner 7. Total-air-entry-hole area, 50.2 square inches.

Figure 7. - Concluded. Combustor pressure-loss data obtained with various liners installed in 24-inch-diameter housing at various inlet-air pressure and velocity conditions. Inlet-air temperature, 268° F.

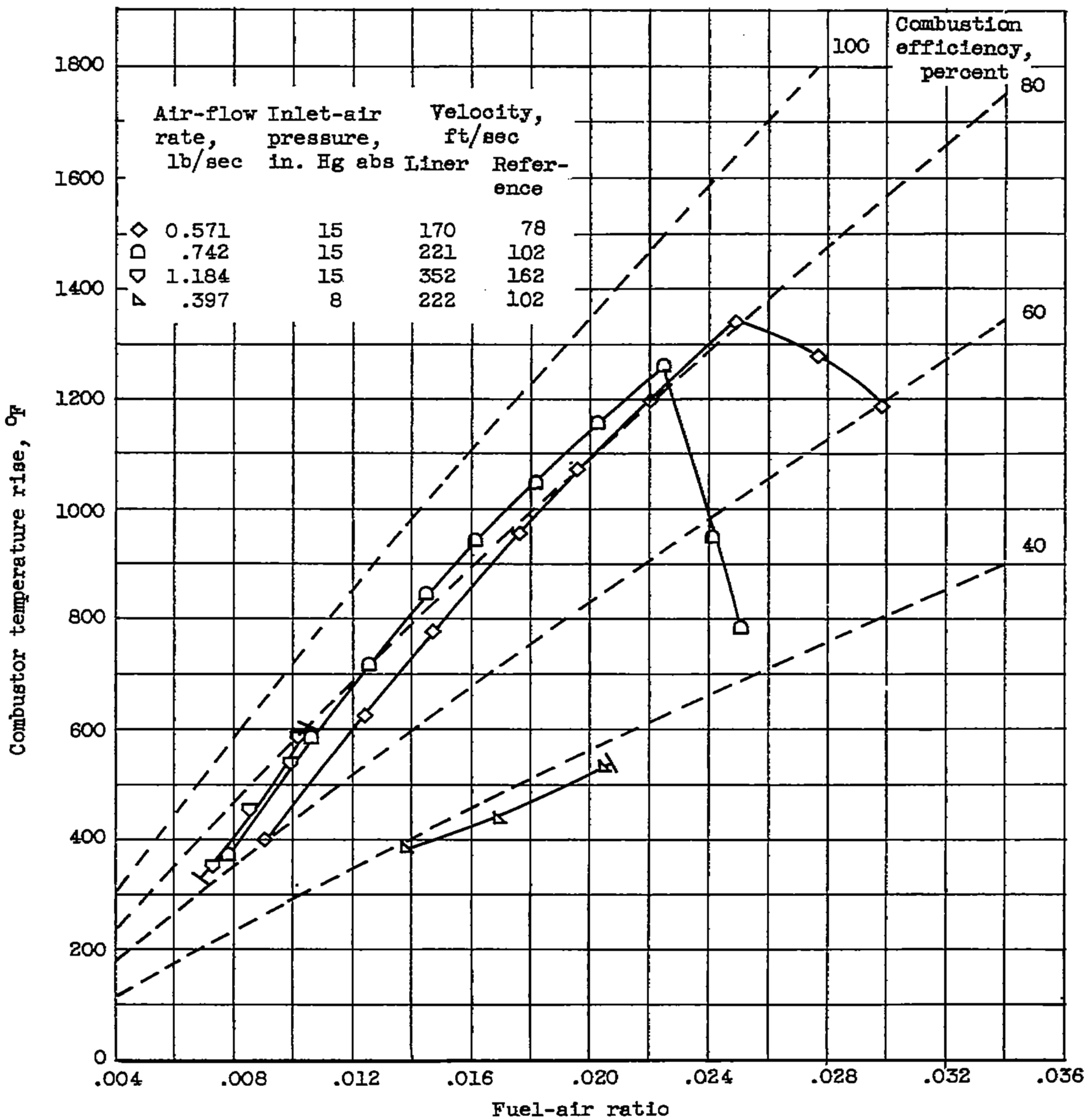
3029



(a) Liner 1, with air-guide tubes at upstream air holes.

Figure 8. - Combustor temperature-rise data obtained with various liners installed in 7-inch-diameter housing at various inlet-air pressure and velocity conditions. Inlet-air temperature, 268° F.

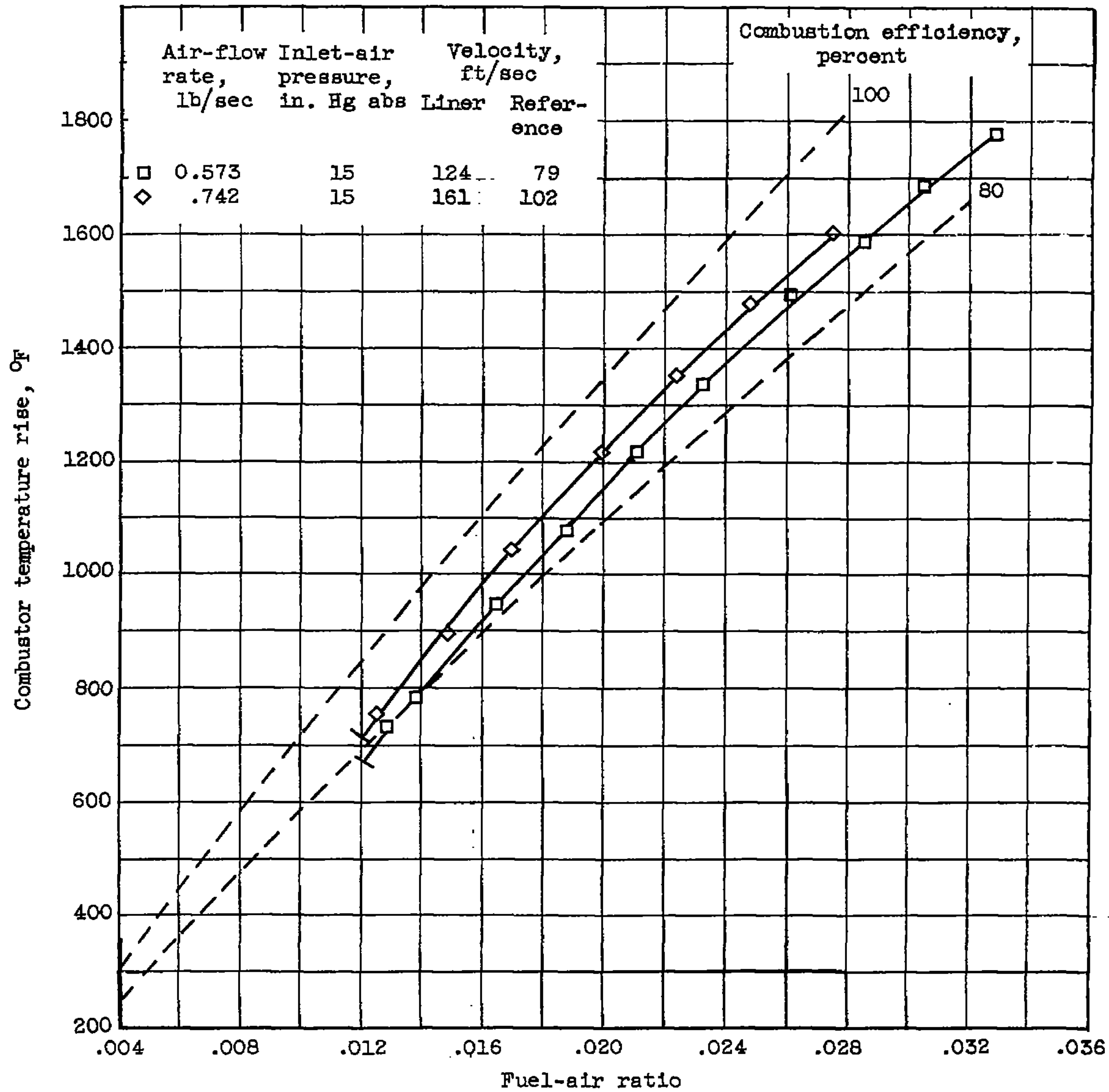
3029



(b) Liner 1, without air-guide tubes.

Figure 8. - Continued. Combustor temperature-rise data obtained with various liners installed in 7-inch-diameter housing at various inlet-air pressure and velocity conditions. Inlet-air temperature, 268° F.

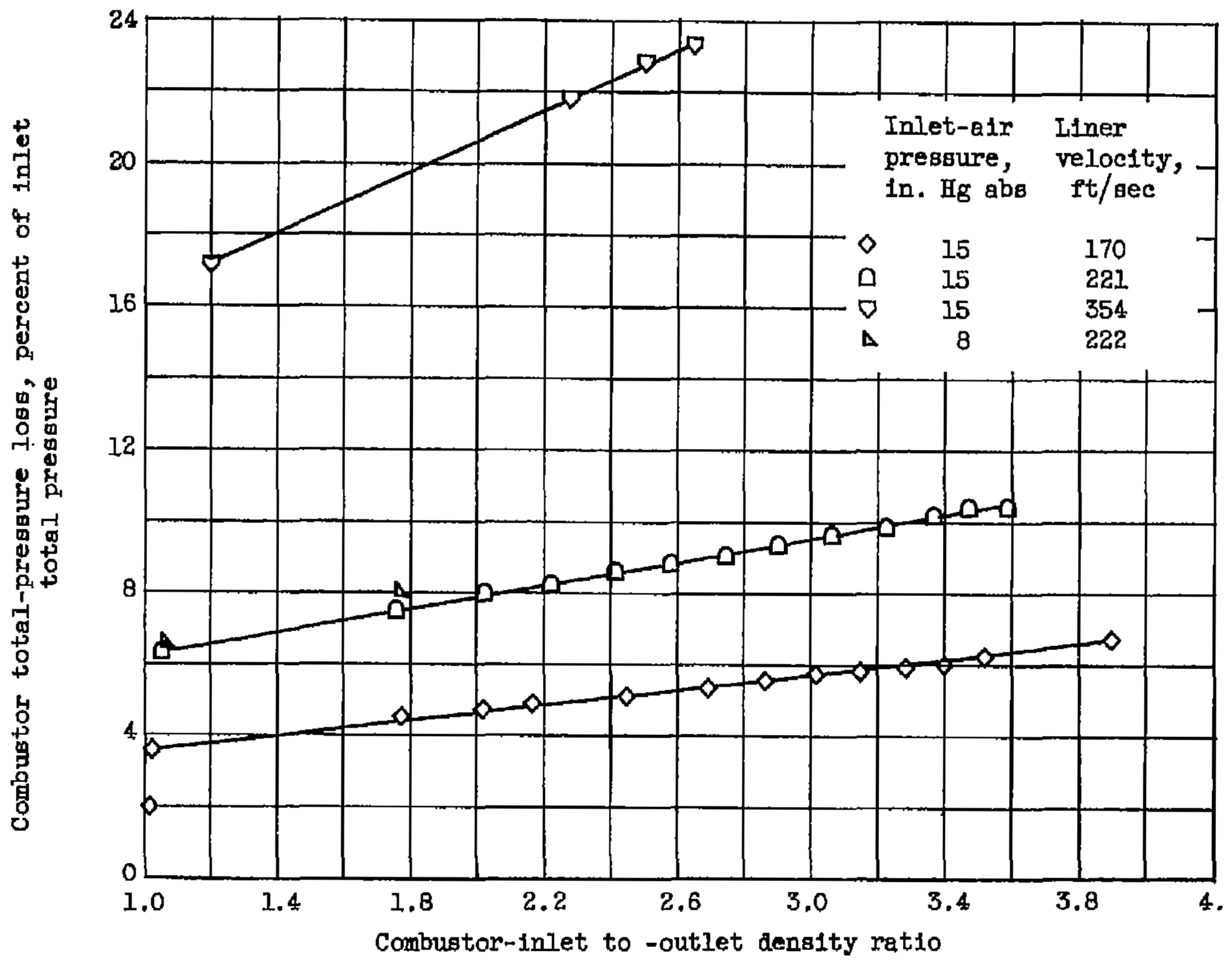
3029



(c) Liner 2, with air-guide tubes at upstream air holes.

Figure 8. - Concluded. Combustor temperature-rise data obtained with various liners installed in 7-inch-diameter housing at various inlet-air pressure and velocity conditions. Inlet-air temperature, 268° F.

[redacted]



(a) Liner 1, with air-guide tubes at upstream air holes.

Figure 9. - Combustor pressure-loss data obtained with various liners installed in 7-inch-diameter housing at various inlet-air pressure and velocity conditions. Inlet-air temperature, 268° F.

[redacted]

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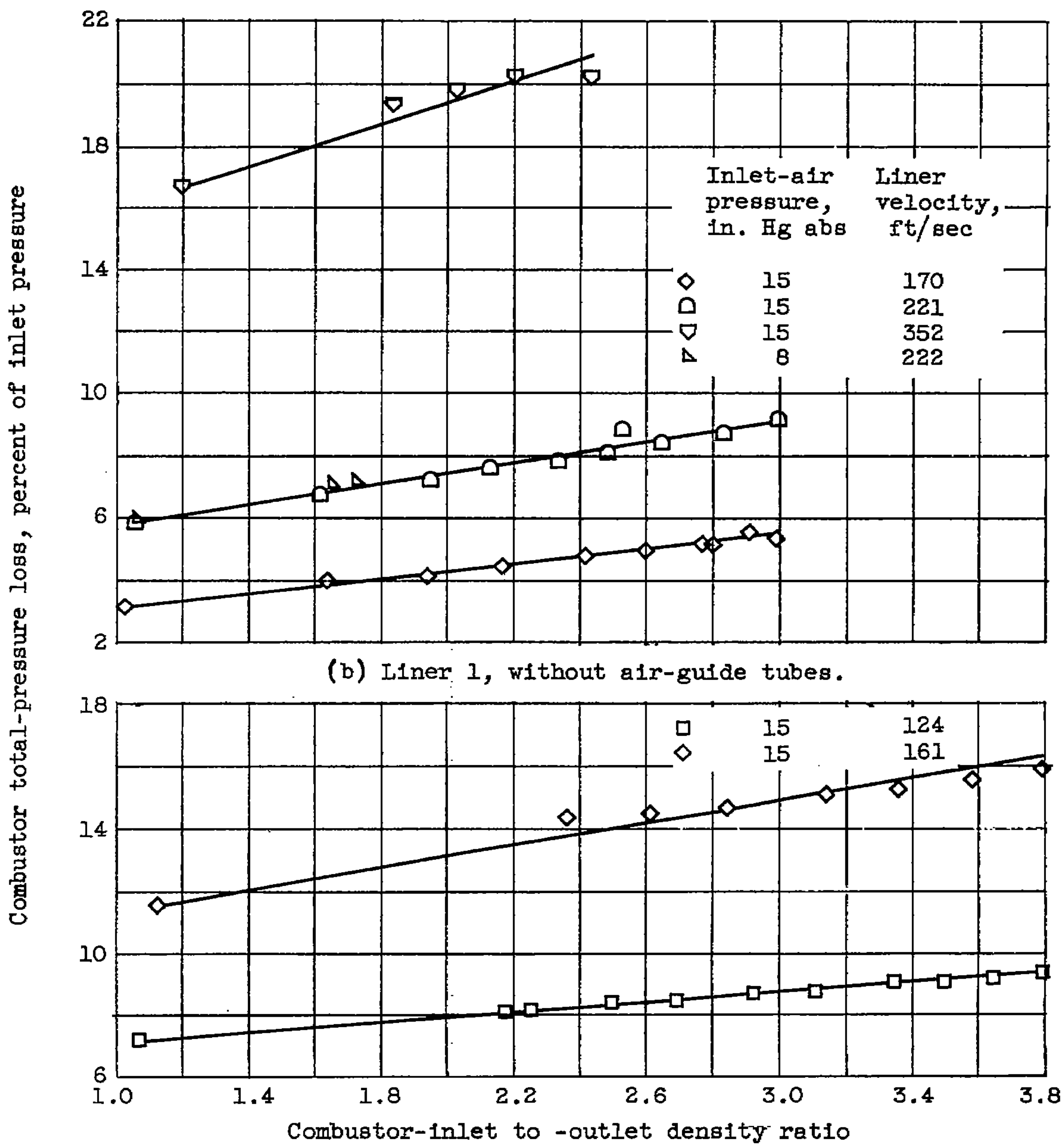
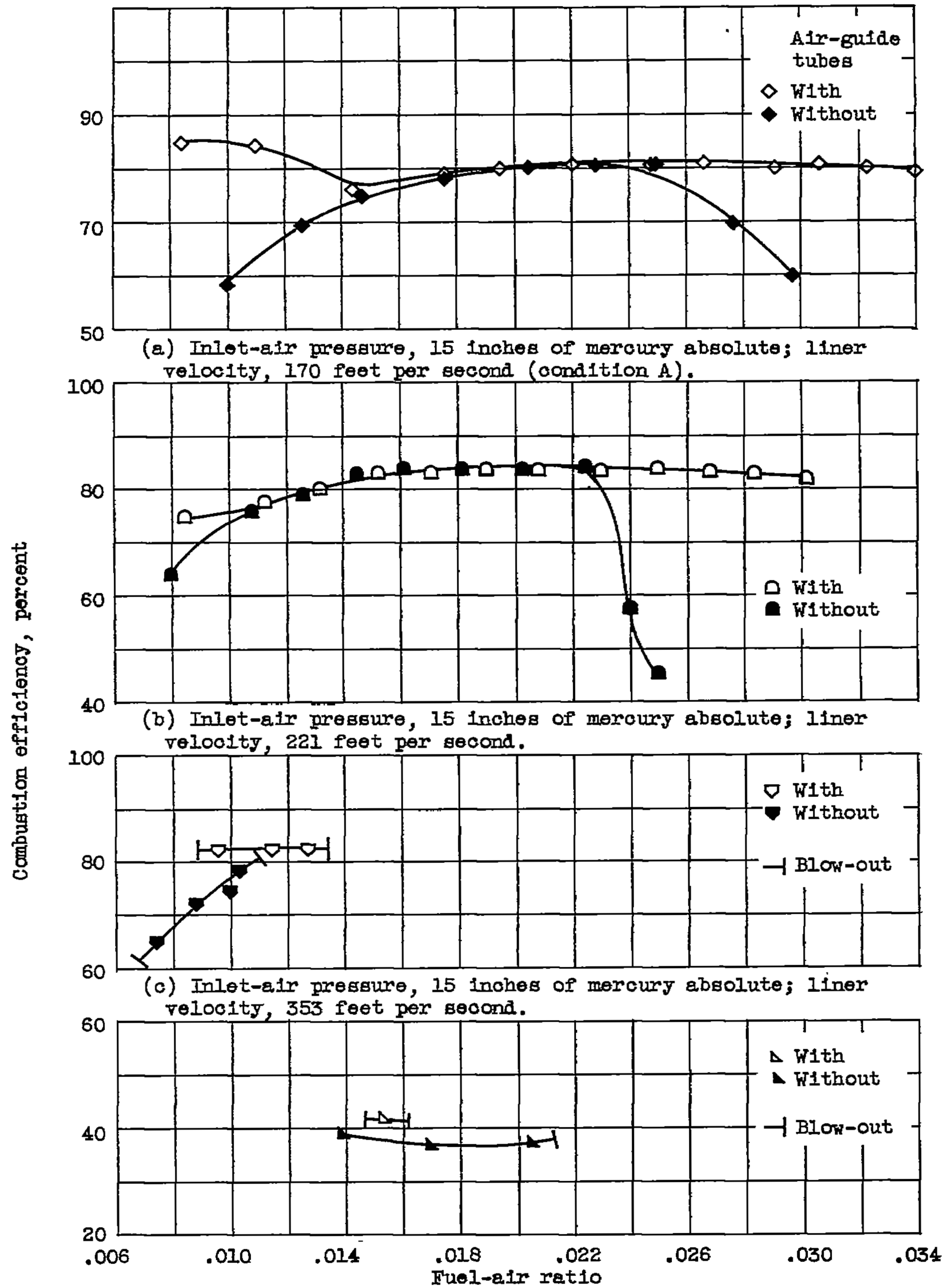


(b) Liner 1, without air-guide tubes.

(c) Liner 2, with air-guide tubes at upstream air holes.

Figure 9. - Concluded. Combustor pressure-loss data obtained with various liners installed in 7-inch-diameter housing at various inlet-air pressure and velocity conditions. Inlet-air temperature, 268° F.

3029



(a) Inlet-air pressure, 15 inches of mercury absolute; liner velocity, 170 feet per second (condition A).

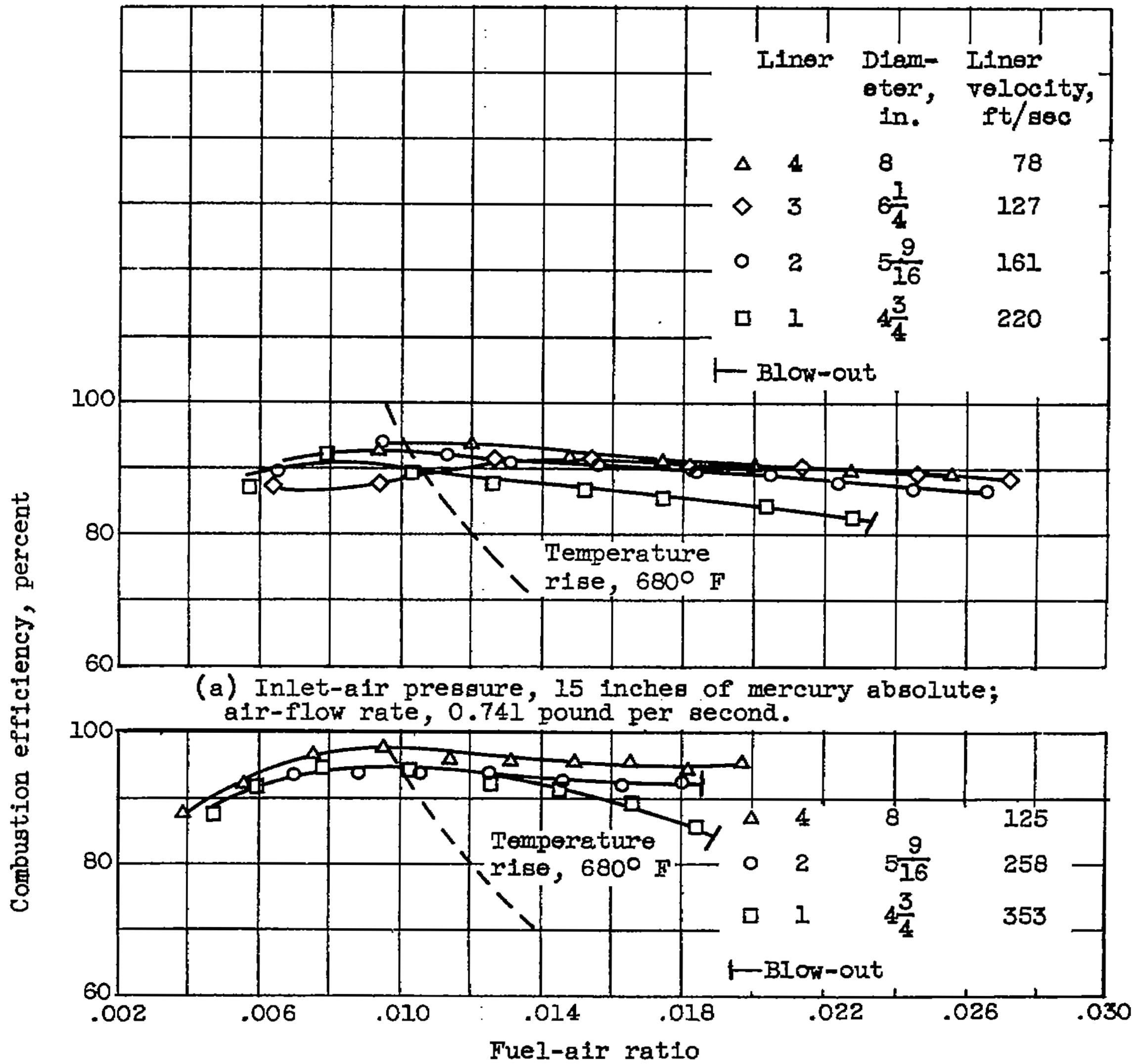
(b) Inlet-air pressure, 15 inches of mercury absolute; liner velocity, 221 feet per second.

(c) Inlet-air pressure, 15 inches of mercury absolute; liner velocity, 353 feet per second.

(d) Inlet-air pressure, 8 inches of mercury absolute; liner velocity, 222 feet per second.

Figure 10. - Effect of air-guide tubes at upstream air holes on combustion efficiency of liner 1 installed in 7-inch-diameter housing at various operating conditions.

3029

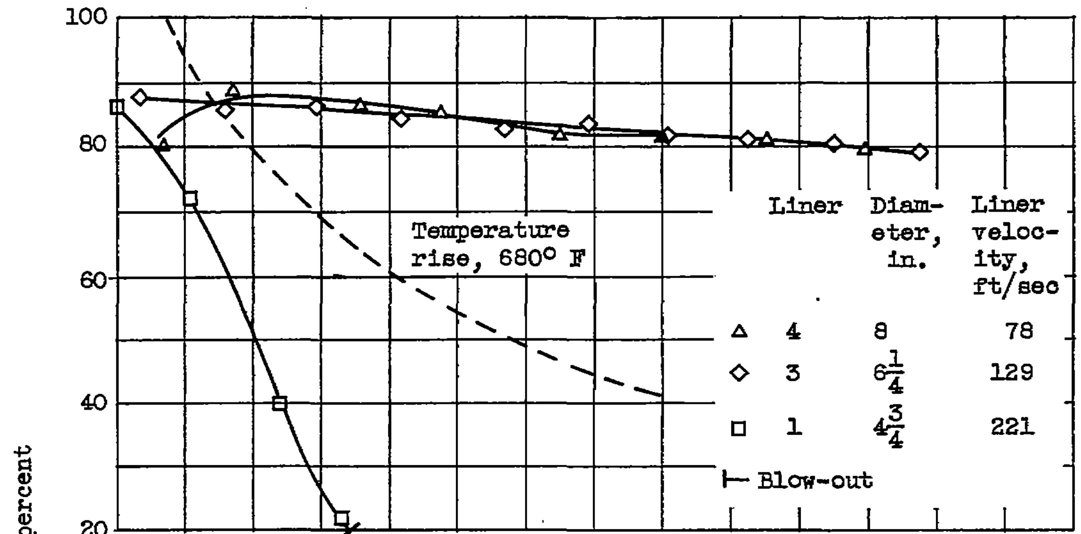


(a) Inlet-air pressure, 15 inches of mercury absolute; air-flow rate, 0.741 pound per second.

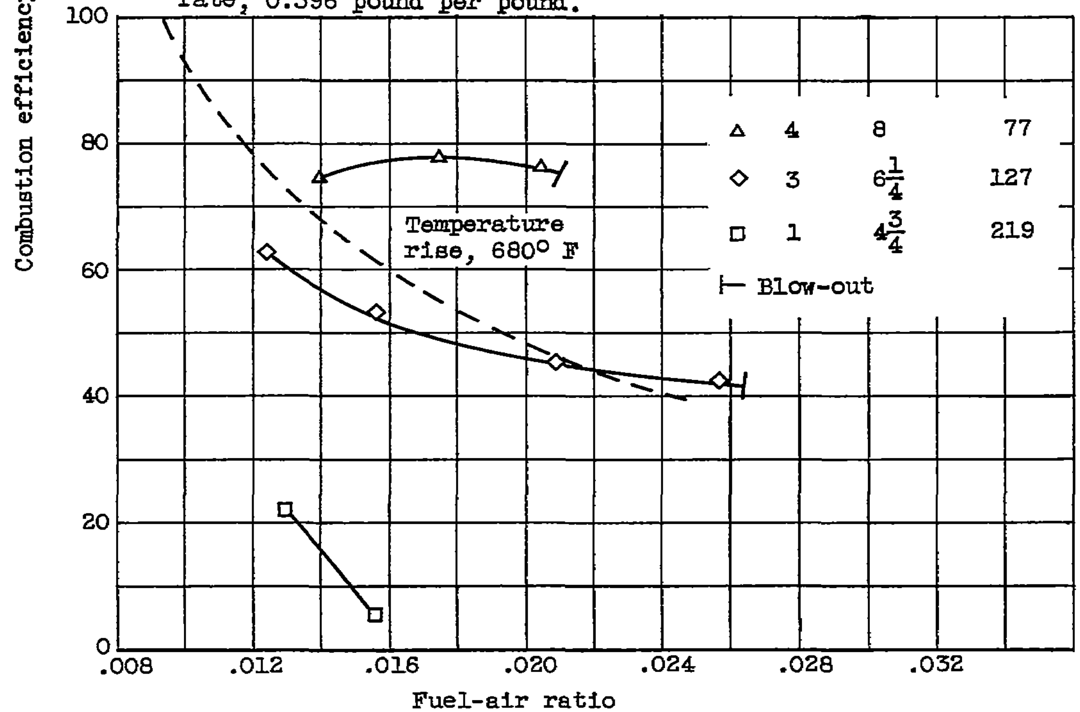
(b) Inlet-air pressure, 15 inches of mercury absolute; air-flow rate, 1.190 pounds per second.

Figure 11. - Comparison of combustion efficiency of liners of different diameter installed in 24-inch-diameter housing at constant mass-air-flow rates and various inlet-air pressures.

3029



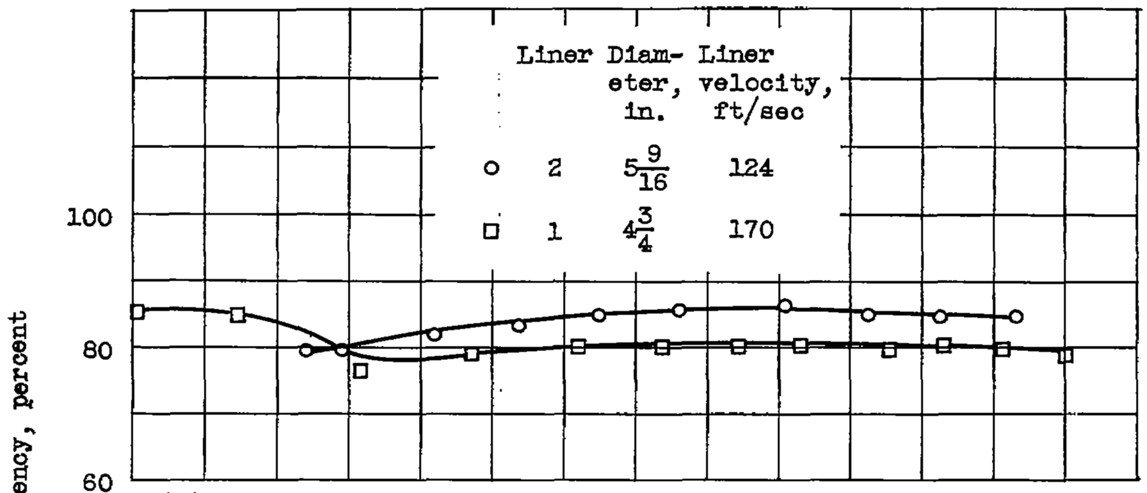
(c) Inlet-air pressure, 8 inches of mercury absolute; air-flow rate, 0.396 pound per pound.



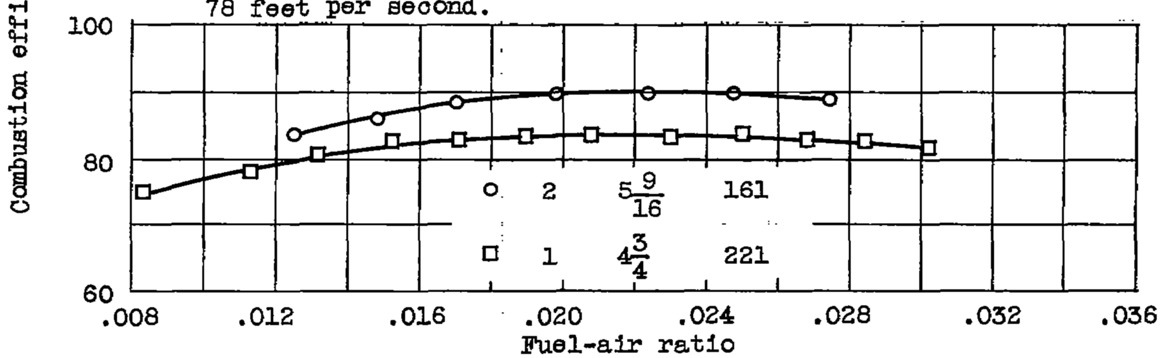
(d) Inlet-air pressure, 5 inches of mercury absolute; air-flow rate, 0.246 pound per second.

Figure 11. - Concluded. Comparison of combustion efficiency of liners of different diameter housing in 24-inch-diameter housing at constant mass-air-flow rates and various inlet-air pressures.

3029



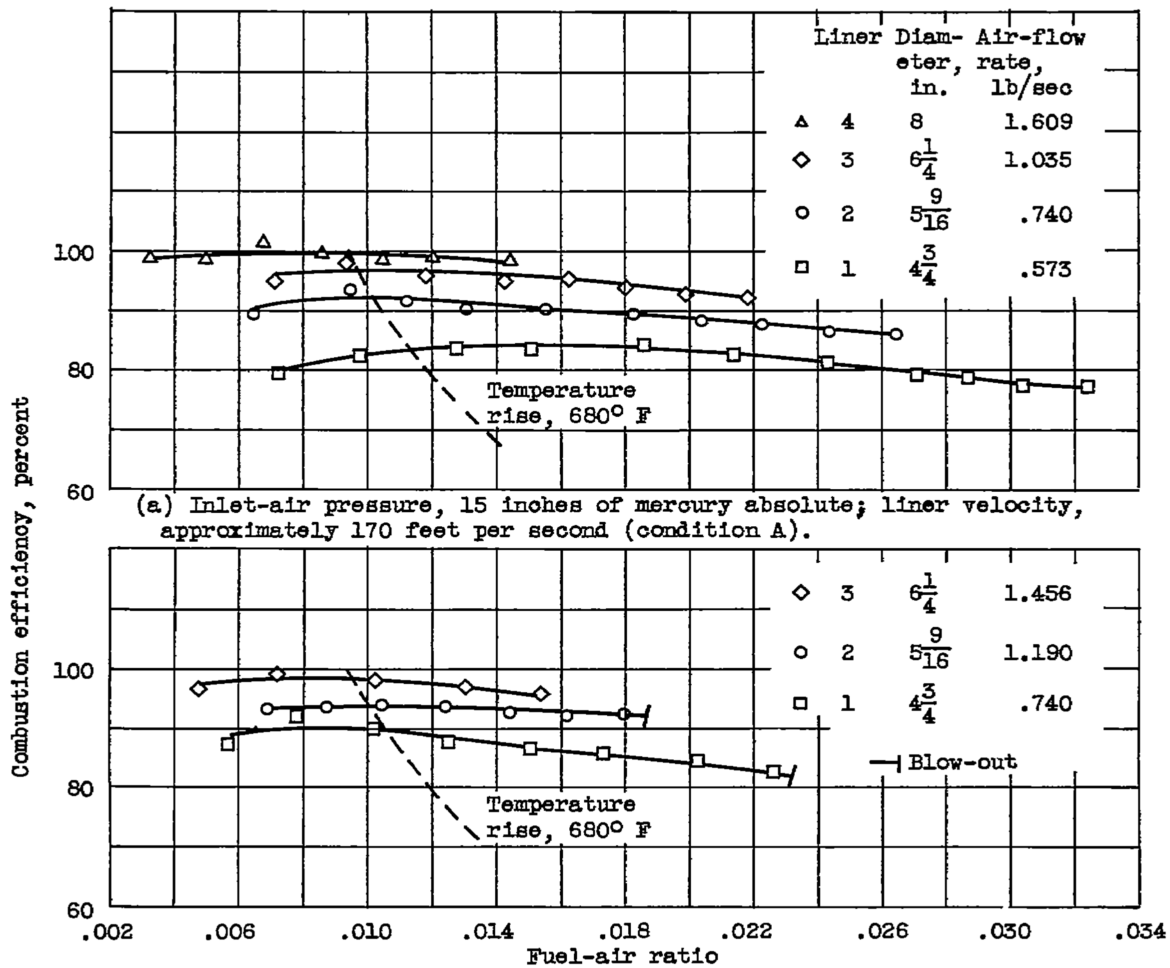
(a) Air-flow rate, 0.572 pound per second; reference velocity, 78 feet per second.



(b) Air-flow rate, 0.742 pound per second; reference velocity, 102 feet per second.

Figure 12. - Comparison of combustion efficiency of liners of different diameter installed in 7-inch-diameter housing at constant mass-air-flow rates. Inlet-air pressure, 15 inches of mercury absolute; inlet-air temperature, 268° F.

3029

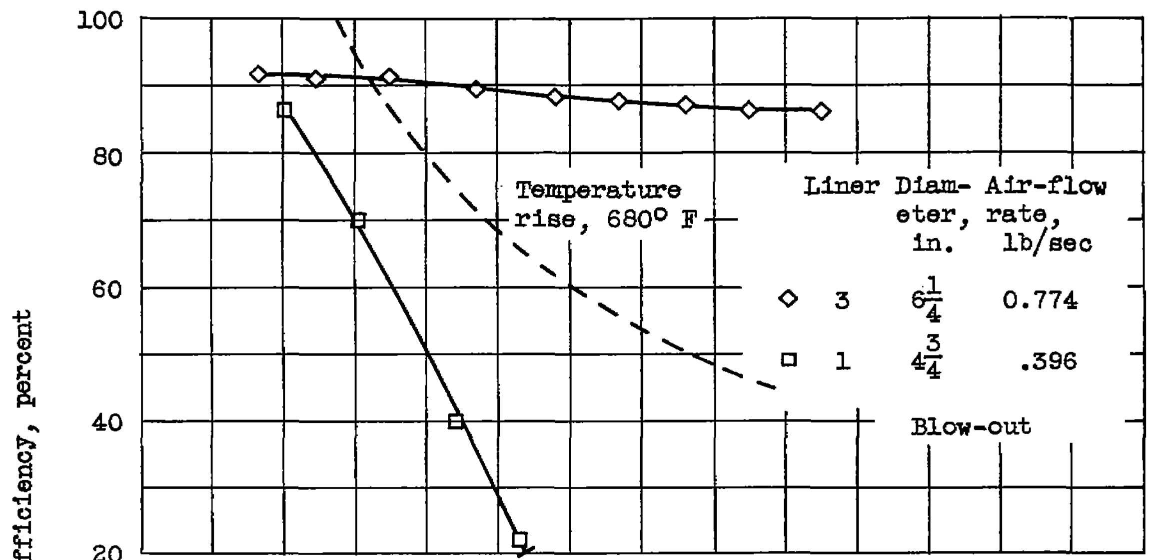


(a) Inlet-air pressure, 15 inches of mercury absolute; liner velocity, approximately 170 feet per second (condition A).

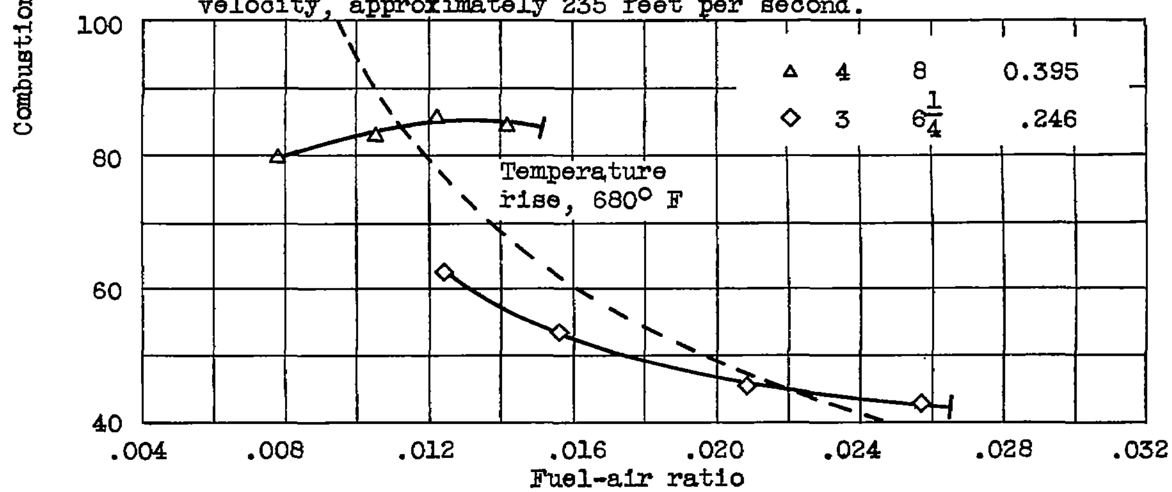
(b) Inlet-air pressure, 15 inches of mercury absolute; liner velocity, approximately 250 feet per second.

Figure 13. - Comparison of combustion efficiency of liners of different diameter installed in 24-inch-diameter housing at approximately constant liner velocity.

3029



(c) Inlet-air pressure, 8 inches of mercury absolute; liner velocity, approximately 235 feet per second.



(d) Inlet-air pressure, 5 inches of mercury absolute; liner velocity, approximately 125 feet per second.

Figure 13. - Concluded. Comparison of combustion efficiency of liners of different diameter installed in 24-inch-diameter housing at approximately constant liner velocity.

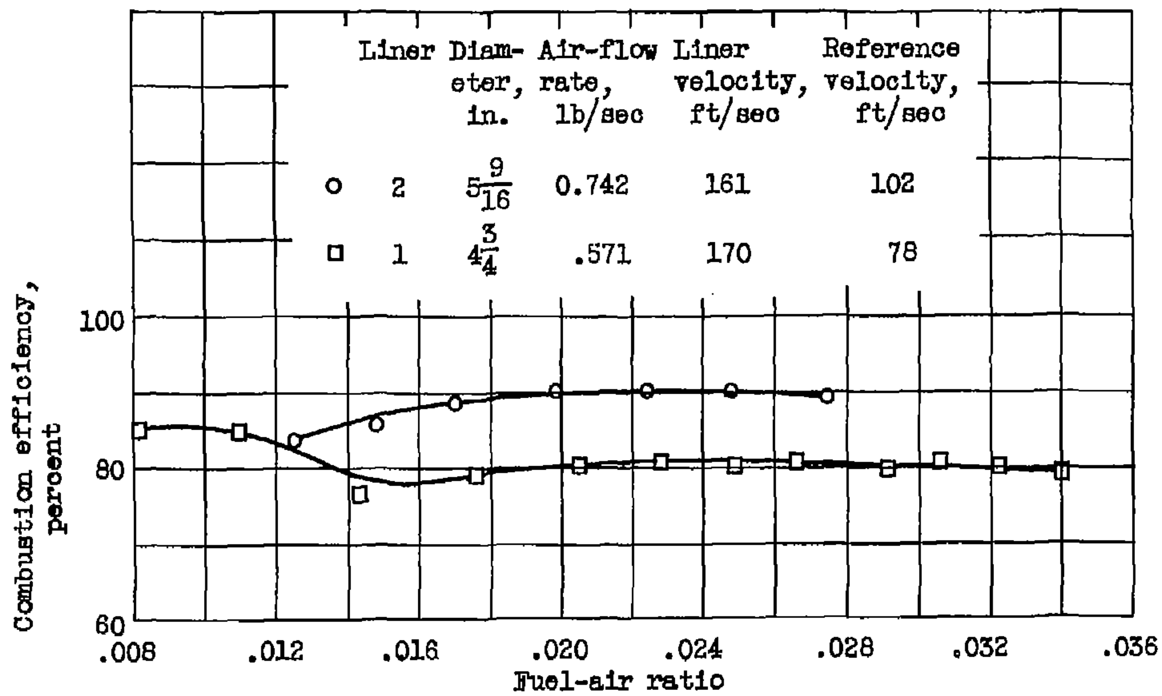
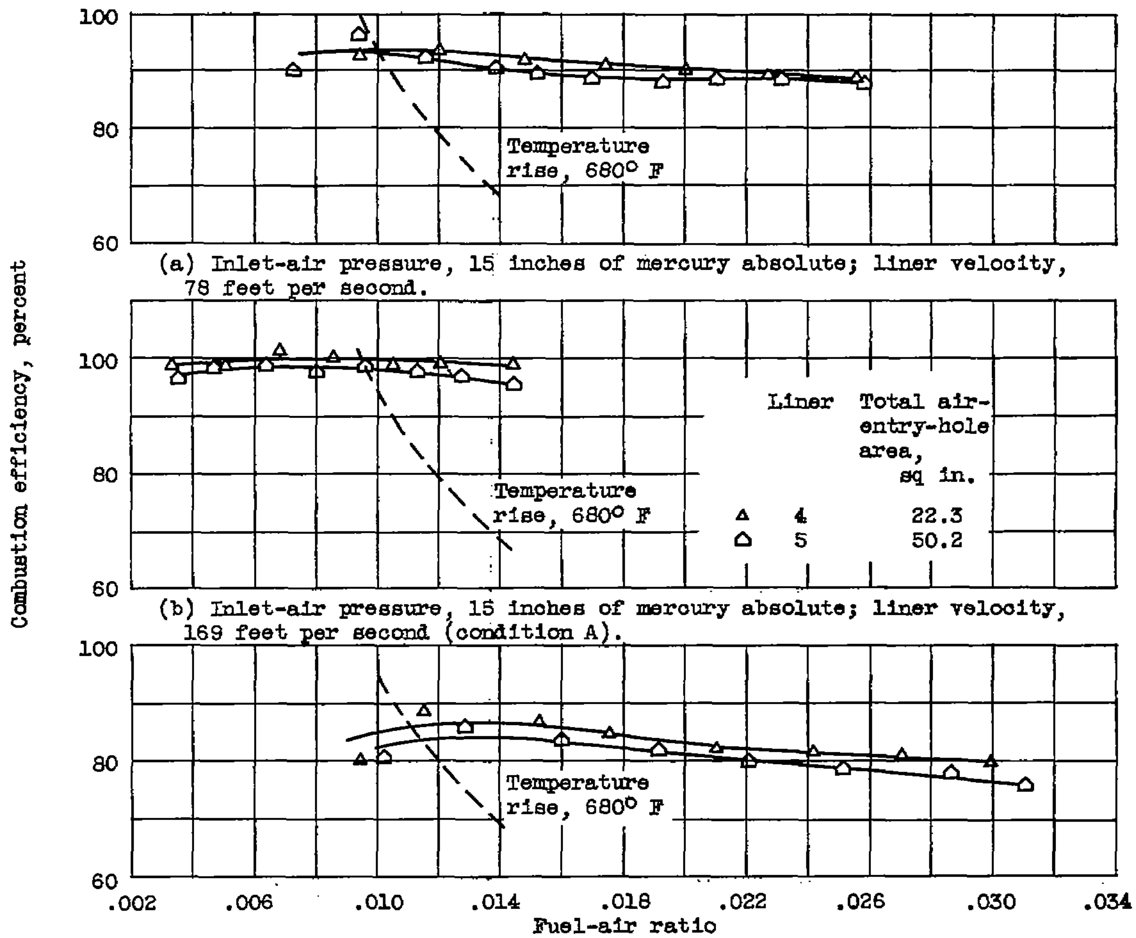


Figure 14. - Comparison of combustion efficiency of liners of different diameter installed in 7-inch-diameter housing at approximately constant liner velocity. Inlet-air pressure, 15 inches of mercury absolute; inlet-air temperature, 268° F.

3029



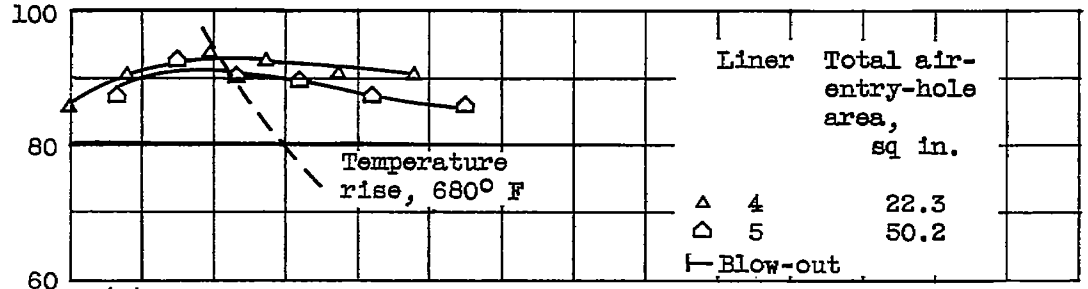
(a) Inlet-air pressure, 15 inches of mercury absolute; liner velocity, 78 feet per second.

(b) Inlet-air pressure, 15 inches of mercury absolute; liner velocity, 169 feet per second (condition A).

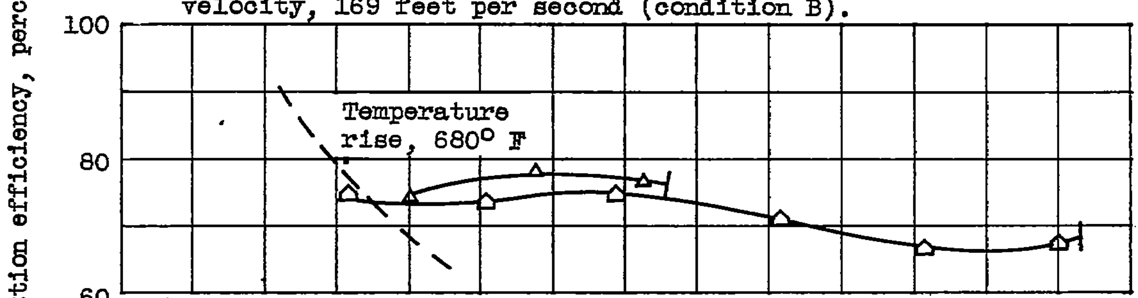
(c) Inlet-air pressure, 8 inches of mercury absolute; liner velocity, 78 feet per second.

Figure 15. - Comparison of combustion efficiency at various operating conditions for two 8-inch-diameter liners differing in total air-entry-hole area.

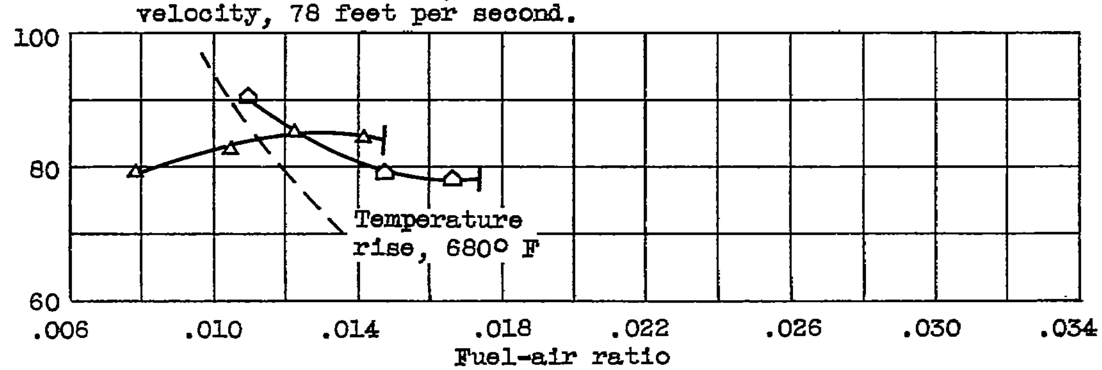
3029



(d) Inlet-air pressure, 8 inches of mercury absolute; liner velocity, 169 feet per second (condition B).



(e) Inlet-air pressure, 5 inches of mercury absolute; liner velocity, 78 feet per second.



(f) Inlet-air pressure, 5 inches of mercury absolute; liner velocity, 125 feet per second.

Figure 15. - Concluded. Comparison of combustion efficiency at various operating conditions for two 8-inch-diameter liners differing in total air-entry-hole area.

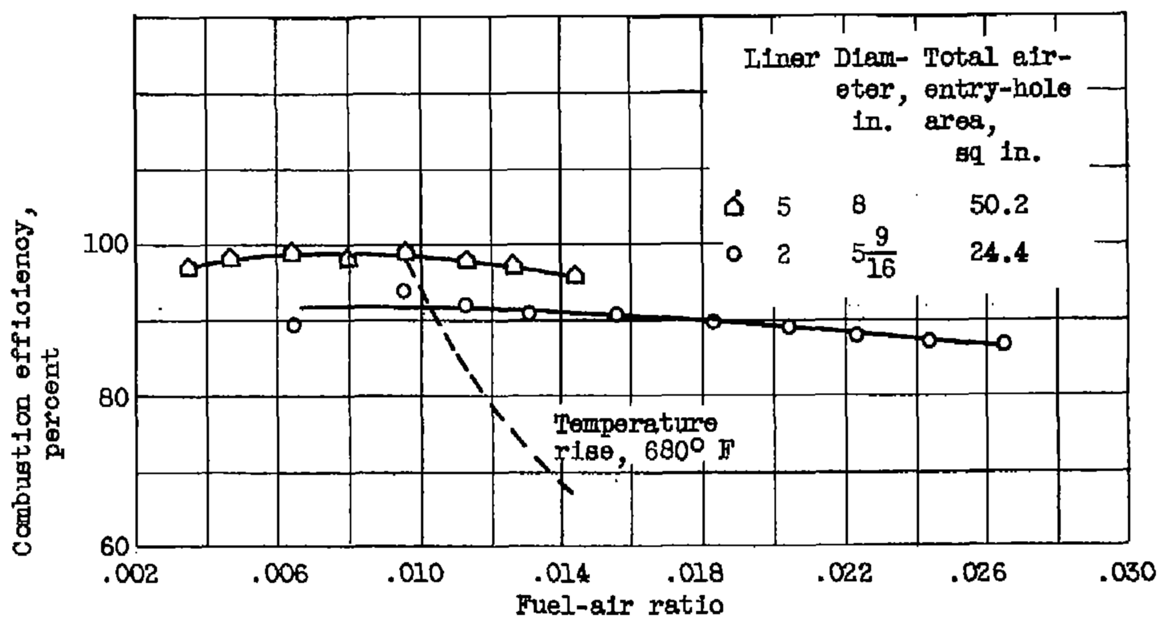


Figure 16. - Comparison of combustion efficiency obtained at condition A with liners of different diameter having total air-entry-hole areas scaled to liner cross-sectional areas.

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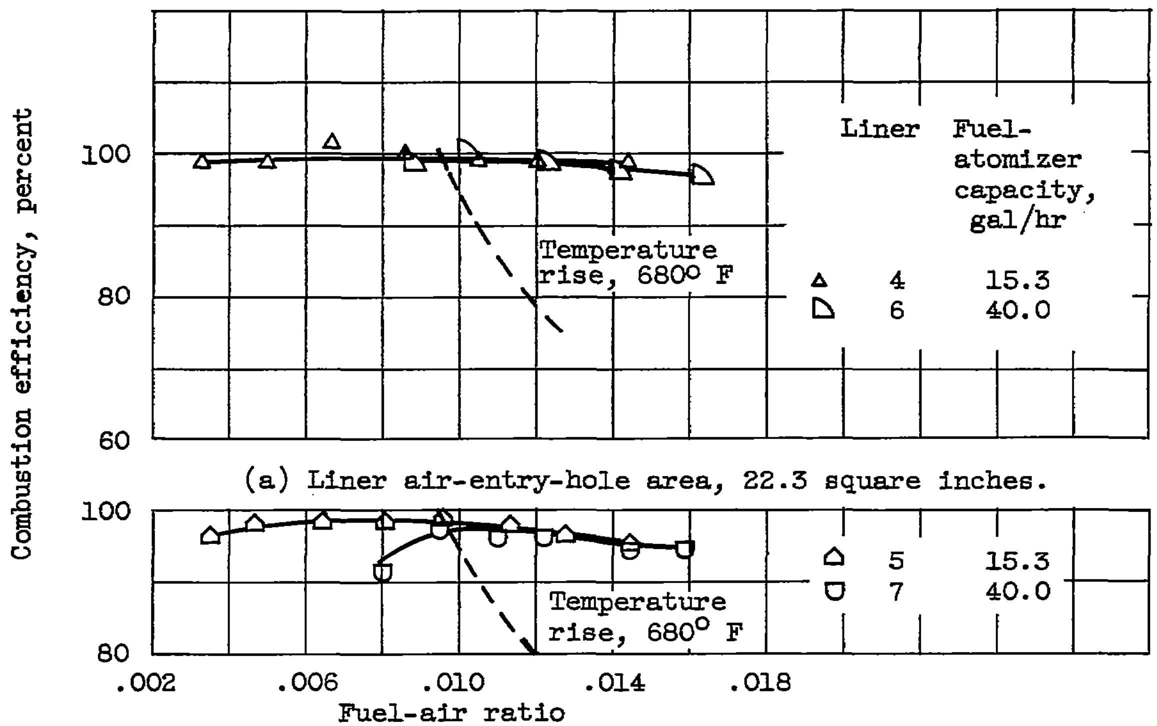

(b) Liner air-entry-hole area, 50.2 square inches.

Figure 17. - Comparison of combustion efficiency at condition A for two 8-inch-diameter liners differing in fuel-atomizer capacity.

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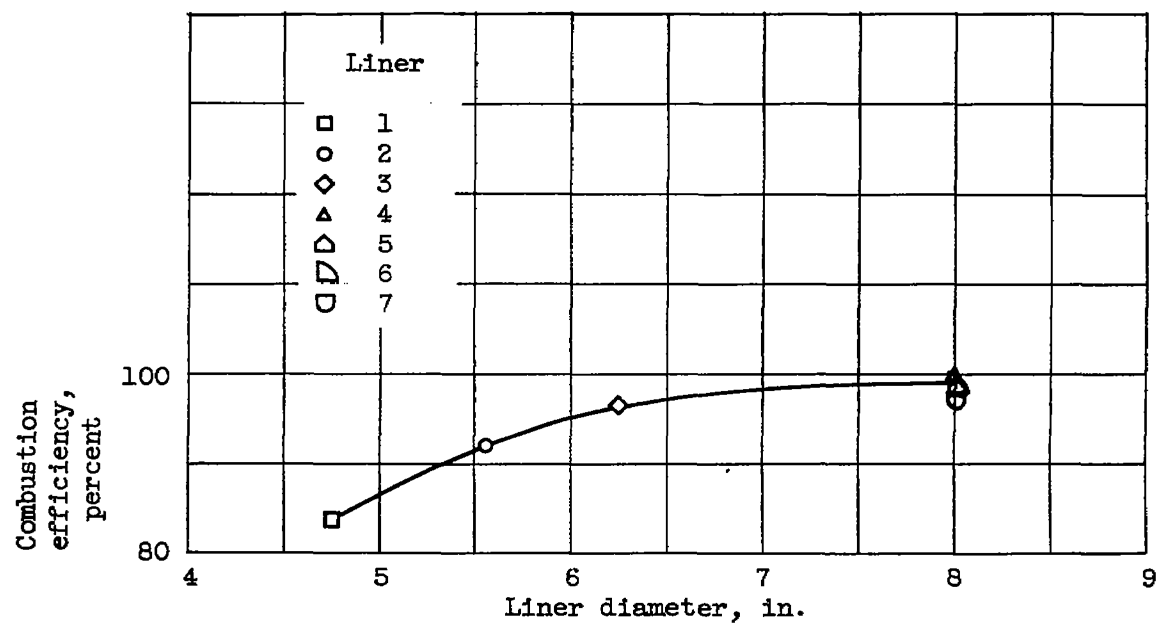

Figure 18. - Variation of combustion efficiency with liner diameter at operating condition A.

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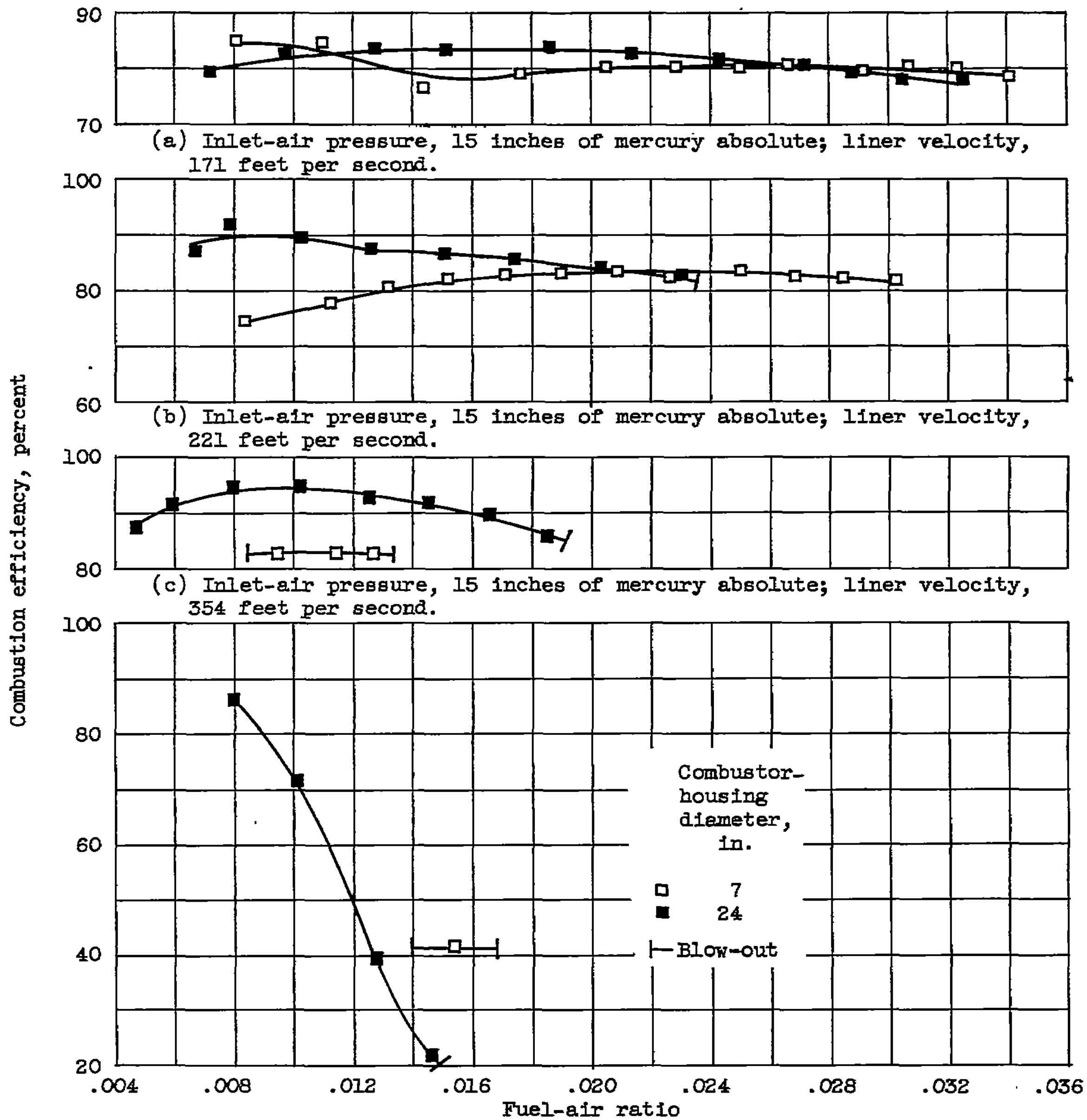


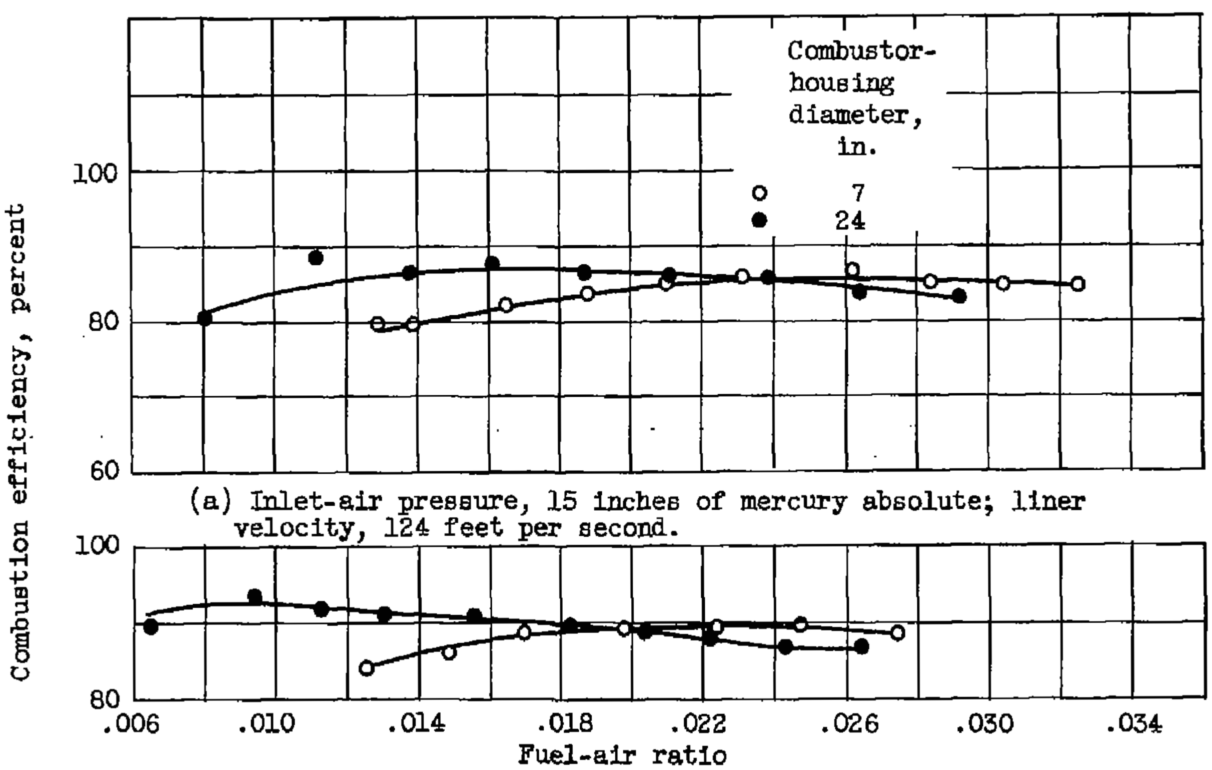
(a) Inlet-air pressure, 15 inches of mercury absolute; liner velocity, 171 feet per second.

(b) Inlet-air pressure, 15 inches of mercury absolute; liner velocity, 221 feet per second.

(c) Inlet-air pressure, 15 inches of mercury absolute; liner velocity, 354 feet per second.

(d) Inlet-air pressure, 8 inches of mercury absolute; liner velocity, 222 feet per second.

Figure 19. - Effect of combustor-housing diameter on combustion efficiency of liner 1 at various operating conditions.



(a) Inlet-air pressure, 15 inches of mercury absolute; liner velocity, 124 feet per second.

(b) Inlet-air pressure, 15 inches of mercury absolute; liner velocity, 161 feet per second.

Figure 20. - Effect of combustor-housing diameter on combustion efficiency of liner 2 at various operating conditions.

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